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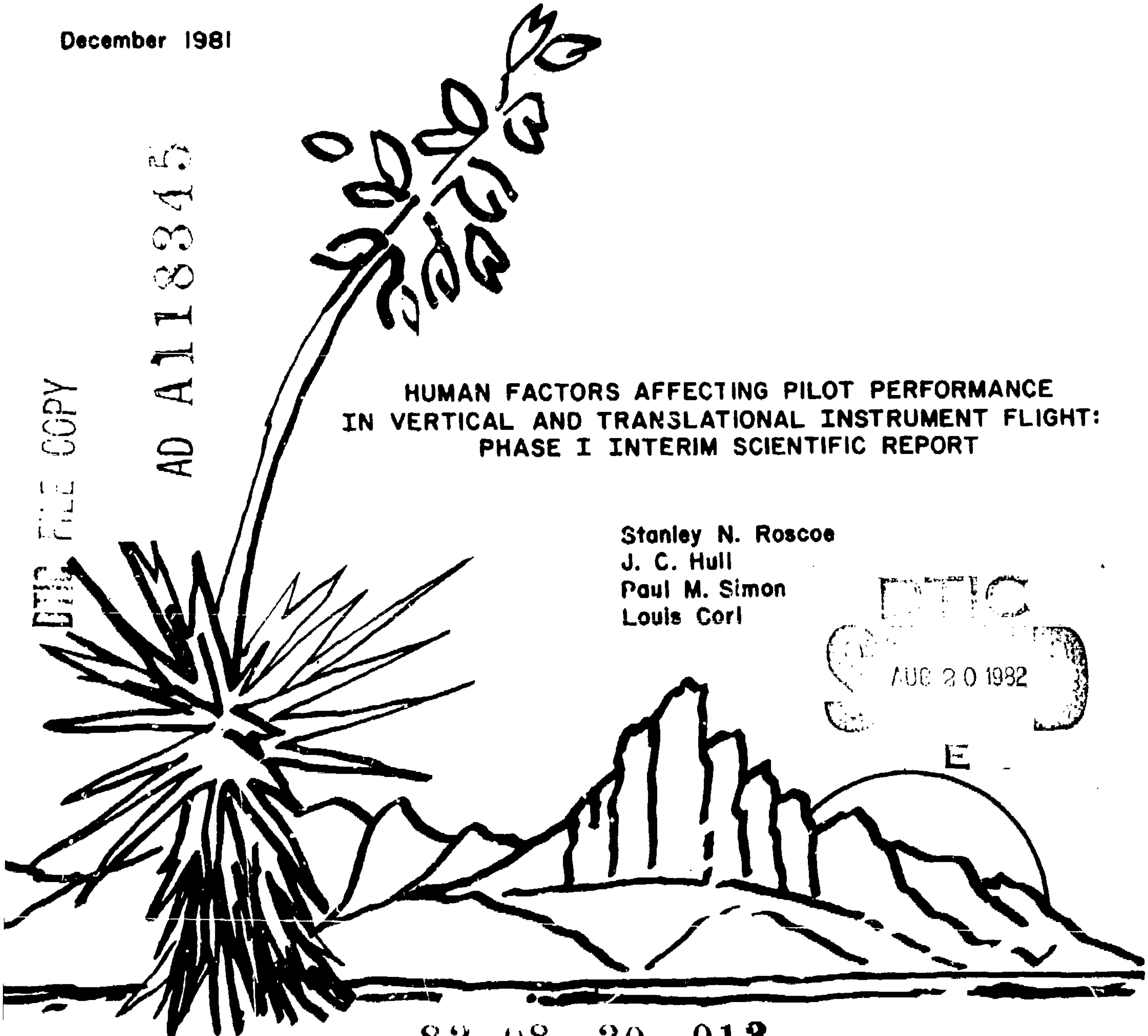

HUMAN FACTORS AFFECTING PILOT PERFORMANCE IN VERTICAL AND TRANSLATIONAL INSTRUMENT FLIGHT: PHASE I INTERIM SCIENTIFIC REPORT

Stanley N. Roscoe
J. C. Hull
Paul M. Simon
Louis Corl

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A conceptual analysis and review of human factors problems in piloting VTOL aircraft including helicopters is presented. VTOL mission and flight requirements are contrasted with those of CTOLs. Deficiencies in present VTOL flight instrumentation are detailed. The requirement that information regarding ground-referenced and airmass-referenced position in all six degrees of freedom be presented to the VTOL pilot and/or incorporated into positional control stabilization is stated. An experimental approach that is based on established

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BEHAVIORAL ENGINEERING LABORATORY

Department of Psychology
Box 5095/Las Cruces, New Mexico 88003
Telephone (505) 646-4716

NEW MEXICO STATE UNIVERSITY

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EXECUTIVE SUMMARY

Problem and Approach

Consider the hawk and the hummingbird and by way of analogy the conventional fixed-wing airplane and the various VTOL airplanes including helicopters.* Conventional airplanes, like hawks, are supported largely by aerodynamic lift and can soar and glide great distances without movement or propulsive thrust. VTOL airplanes, like hummingbirds, can't soar nor can they glide far, and they depend on propulsive thrust to maintain airborne flight. But hummingbirds and VTOLs are not without advantages for their degrees of maneuvering freedom far exceed those of hawks and fixed-wing airplanes.

The problem with VTOL airplanes and helicopters is how to take advantage of their ability to fly like hummingbirds in the execution of missions totally beyond the capabilities of fixed-wing airplanes, and to do so in bad weather and at night. Progress toward this objective has been relatively slow, largely because of the traditional view that thrust-borne vertical and translational flight is merely a special case of aerodynamic flight. Consequently, almost by default, flight instrumentation for helicopters and vectored-thrust VTOLs has consisted of hand-me-down adaptations of conventional instruments that were only marginally acceptable for their original functions.

Our approach is to view thrust-borne vertical and translational flight as the general case and aerodynamic lift and drag merely as special effects of high velocities in certain configurations. Thus we take it that future mission functions can and will involve some independence of control of all six degrees of maneuvering freedom within whatever limits may be designed into a particular airplane. We further assume that the state of the instrumentation art either allows or soon will allow any physical variable of flight--including positions, rates, accelerations, and electromechanical performance--to be sensed with any degree of precision and reliability required.

Having cleared the deck of the problems that historically have claimed most of our research and development funds and attention, we will focus on what information is needed and how best to integrate and encode it to let us fly in bad weather and at night like hummingbirds do in good weather during the day. Although there is a relatively large literature on helicopter and VTOL flight instrumentation, there are surprisingly few reports that deal with the subject as we propose. Consequently, our chief sources of relevant information are a few reports and

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* Although helicopters can take off and land vertically, we will use the term VTOL hereafter to refer to aircraft whose vertical flight capability depends on vectored thrust rather than that produced by a rotary wing.

a few individuals who have extensive technical and operational experience and happen to share our philosophy and objectives.**

Missions and Mission Requirements

VTOL and helicopter missions include some common elements and some elements unique to each. Whereas VTOLs are capable of supersonic fighter-attack missions as well as those involving very low speeds, helicopters perform only in low-speed regimes, but they can sustain very low-speed flight for a much longer time. Consequently helicopters can perform a number of naval missions that require precise control of position over the ground or sea, while VTOLs, because of their limited time in thrust-borne flight, make practical use of their hovering capability mainly in shipboard takeoffs and landings.

Functional requirements for fighter-attack VTOL missions are unlike those of other fighter-attack missions in that they involve increasingly greater independence of flight attitude and motion. Within limits VTOLs can point in one direction while moving in another, particularly at slow speeds, and this capability is of great value in air combat maneuvering and ground attack. Although these missions are normally conducted in fair weather, displays are needed that show the relationships among possible, desired, and actual positions, rates, and accelerations.

Functional requirements for helicopter operations derive mainly from the family of missions that involves rapid transitions from one ground-referenced stationary position to another. Examples include anti-submarine sonar-dipping, nap-of-the-earth flight, and air-sea rescue operations. In each case the relationships between earth-referenced and airmass-referenced positions, rates, and accelerations must be controlled, and once again actual, desired, and possible values must be taken into account. The basic functional requirement is to fly directly from one hover point to another with any desired heading regardless of the wind; this cannot be done safely on instruments at present.

Deficiencies in Current Instrumentation

The heart of the instrumentation problems with both VTOLs and helicopters has always been the instabilities inherent in conventional control systems. Any realistic hope of achieving the vertical and translational maneuvering potential of these airplanes must start with the adoption of control systems that provide not only stability but direct maneuvering performance control. The Navy's AV-8B airplane represents a major advance in VTOL stability augmentation, and similar slow advances are being made in stabilizing helicopter control. The degree

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** Individuals who have contributed substantially to this analysis include: CAPT William O. Wirt (USN, Ret.), CDR Kent Hull (ONR, Code 230), LTC Paul G. Stringer (USA, Ret.), and Dr. Lloyd Hitchcock, Jr. (FAA Technical Center).

of direct maneuvering performance control contemplated here would go well beyond current advances.

As progress is made in stabilizing vertical and translational control systems and thereby unburdening the pilot, the deficiencies of current VTOL and helicopter display systems become both more readily apparent and easily addressed. The biggest shortcoming, in the view of thinking operational people, is the traditional attempt, never wholly successful, to present dynamic information on slowly changing position indicators that force the pilot to differentiate rates and accelerations. Furthermore, such displays are, with few exceptions such as airspeed and angle-of-attack indicators, space-referenced only and not airmass-referenced, as they also need to be. One retired Navy Captain suggested a "snowstorm display" to depict speed of movement through the airmass (William O. Wirt, personal communication).

The same former Navy helicopter flight test director reported that, between the mid-1950s and 1976, there were more than 700 helicopter collisions with the surface (land or water) and that his analysis attributed about 60 percent directly to deficiencies in cockpit instrumentation. He also noted that cockpit instrumentation was never given as a "cause/factor" in the reports of these accidents and that the vast majority were attributed to "pilot error." His conclusion was that helicopter pilots need an "integrated presentation of spatial motion relative both to the airmass and to the surface, including height." Another authority on naval operations asserted that from 1973 to 1978 there was no advance in helicopter or VTOL aircraft capability in poor weather or at night.

Information Requirements

In the most general sense, it is evident that what is needed both in VTOLs and helicopters are integrated forward-looking and downward-looking presentations of the position, rate, and acceleration of the vehicle relative to the external world in all six dimensions of motion. Furthermore, all of these variables either have to be presented in relation to the airmass (how to do this effectively is difficult to imagine despite the snowstorm suggestion) or the effects of airmass movement and turbulence have to be neutralized by means of inertially referenced control (not difficult to imagine and well within the state of the art). And, of course, the actual values of these variables need to be shown in proper relation to their corresponding desired and possible values, given the airplane's current configuration and performance.

Implementation

Our analytical approach to the implementation of the identified functional and informational mission requirements draws on the basic literature of aviation psychology. Among the best-established applicable display principles are frequency separation and flight-path prediction. The practical embodiment of these complementary principles is achieved by using inertially sensed motion rates and accelerations to present directionally compatible fast-time projections of imminent position in the context of an aircraft-referenced view of relevant objects in the

outside world, as well as indices of desired and possible performance.

Our experimental approach to the implementation of realistic requirements involves the systematic manipulation of dynamic and configurational variables in the computer animation of skeletal perspective views of relevant objects and constraints in that same outside world. The basic problem is, and always has been, the fundamental difficulty of unambiguously representing six dimensions of position and attitude (three each) on any practical number of two-dimensional surfaces. We are concentrating initially on the forward-looking viewpoint and giving secondary attention to the downward-looking view, including basic perceptual questions in the dynamic display of other traffic.

PROBLEM AND APPROACH

Advantages of VTOLs and Helicopters

Vectored-thrust and rotary-wing aircraft are designed to have several performance advantages over conventional takeoff and landing (CTOL) airplanes that stem from their greater maneuverability in all six degrees of spatial freedom. They may take off and land in a variety of modes from restricted areas such as the decks of relatively small air-capable ships and unimproved forward sites. They can hover over land-based or sea-based operations or rescue sites. Perhaps more importantly, because VTOLs and helicopters can fly slowly at low altitudes, correct altitude errors directly, and stop, they are never committed to land until out of fuel, and should be safer than CTOLs.

There is one major, multifaceted, overriding human factors problem with VTOLs and helicopters, however. Their advantages over CTOLs cited above have not been realized operationally. Presently helicopters tend to be operated as if they were fixed-wing aircraft in missions and circumstances for which their inherent performance flexibility could provide significant operational advantages. As for VTOLs, their use has been limited to visual contact operations, and it is generally conceded that AV-8A pilots are cognitively, perceptually, and manually overloaded. This position is supported by the numbers of accidents and their trend (Hemingway, 1978; Hennessy, Sullivan, and Cooles, 1980; Ringland, Craig, and Clement, 1977).

Sources of Difficulty

With either type of aircraft the pilot can become overloaded for many reasons: (a) acceleration control requires extremely rapid reactions, (b) field-of-view requirements during hovering and landing are immense, (c) altitude maintenance during transition is difficult, (d) different control techniques are required during different phases of flight, (e) steep, decelerating, curved approaches increase pilot workload, (f) attitude stability augmentation is generally inadequate, (g) position stability augmentation, including vertical position is not provided, and (h) information about the craft's proximity to control limits is not currently displayed.

The inherent instability of VTOLs and helicopters (see Sweeney, Bailey, and Dowd, 1957; Wellern, 1971) must receive particular weight however as a factor in causing the pilot's workload to be so intolerably high. With VTOLs, uncorrectable amounts of sideslip may develop during transitions between aerodynamic and thrust-borne flight. Ringland and his colleagues (1977) conclude that instability is the underlying cause of the VTOL's unique human factors problems. Furthermore, the VTOL pilot must control more variables than the CTOL pilot, the control characteristics of the plane change radically during transition to and from low-speed flight, and the meaning of information afforded by an indicator may change during the conversion (transition).

Current design philosophies are also responsible for increasing the pilot's workload to an unmanageable level. These philosophies

emphasize system flexibility and therefore assign many system functions to the pilot that might better be done by computers and other automatic devices. As a consequence, an inordinately high level of skill must be depended on for system reliability and safety as well as adequate mission performance. Even though it has been recognized that different displays are needed, those used have been at best adaptations of ones developed for CTOLs. Therefore, it is easily understood why it is widely considered that current control and display systems are inadequate.

Approach

As Williams (1980) summarized his 1947 analysis of the pilot's job:

> Between the knowledge of what control movements to make and the knowledge of the purpose of a mission lie all the areas of information which together result in the accomplished flight. Since the only course of action open to a pilot is through manipulation of the aircraft's controls, it follows that all the information he receives must eventually be filtered down to this level in order for him to participate in the flight at all. These pieces of information somehow work together in an organized way and for purposes of analysis, must be fitted into some descriptive pattern. . . . Thus, the first problem is to break away from the notion of specific ways for presenting information; the second, to try to develop a scheme into which all pieces of information will fit in a logical way. (p. 35)

Following the master's advice, our approach has been to break away from conventional control and display relationships, arrangements, formats, symbologies, and other sacred cows. These have been replaced by the jailbreaking assumption that the state of the instrumentation art can provide indices of any physical variable of flight with any degree of precision and reliability called for. Furthermore, we view thrust-borne vertical and translational flight as the general case and aerodynamic lift and drag merely as augmentation and/or constraints imposed on otherwise free inertial motion. Thus, mission functions can and will involve, within specific airplane design limits, far greater independence of control in all six degrees of maneuvering freedom.

Given these liberating new degrees of experimental freedom, we have undertaken a systematic reorganization of the control of thrust-borne vehicles and the flow and transfer of information within and between the airplane and pilot. A generic thrust-borne moving body (airplane) is being simulated on the Behavioral Engineering Laboratory's versatile MicroGraphic Simulator. Subject to the resistance imposed by aerodynamic drag, and lift if desired, the vehicle will accelerate along or about any of its axes with the "vectored" application of thrust in accordance with whatever performance capabilities are called for in any specified experimental configuration.

Just as different "airplanes" can be created on call, so can various selectable sets of information and display configurations. To study the effects of alternative divisions of decision and control func-

tions between the pilot and computer, any given subset of information variables can be delivered to either or both. As Williams advised almost 35 years ago, our objective is "to develop a scheme into which all pieces of information will fit in a logical way" so that pilots can fly any thrust-borne mission with information presented in accordance with generalizable principles rather than unique inventions.

MISSIONS AND MISSION REQUIREMENTS

Helicopters and VTOL craft are all capable of low-speed flight and vertical takeoffs and landings. However, the inherent differences between these two types of aircraft make them suitable for different missions. Helicopters are more suited to low-speed missions such as nap-of-the-earth, air-sea rescue, and antisubmarine sonar dipping. VTOLs are theoretically capable of performing these missions but their limited time in thrust-borne flight makes them more suitable for high-speed attack missions. These missions impose additional requirements on VTOLs similar to CTOL requirements. Therefore the mission requirements for VTOLs in high-speed attack missions and for helicopters in low-speed missions must each be given special consideration.

It is interesting to note that when analyzing mission requirements most investigators touch briefly, if at all, on the functions that have to be performed by the pilot in accomplishing an aircraft's missions. Almost immediately discussion turns to the need for control stabilization and unburdening and the information the pilot needs but doesn't have. It is as if the writer assumes that everybody knows the pilot's function is to control the airplane safely and precisely at the edges of its performance capabilities and that instrumenting the airplane to allow him to do so is just another engineering problem.

As a practical matter, the missions for which an aircraft is designed largely determine its physical configuration and potential performance. Statements concerning the functions that must be performed by the pilot or by automatic devices are largely concerned with the conditions under which the man-machine system must operate. With helicopters and VTOLs it is frequently the case that stated mission requirements can be met only under highly favorable conditions. Our objective in this program is to make it possible for pilots to control helicopters and VTOLs throughout the ranges of their potential performance envelopes without restrictions due to adverse ambient conditions.

DEFICIENCIES IN CURRENT INSTRUMENTATION

Controls

Instrumentation deficiencies in helicopters and VTOLs are the principal factors preventing these craft from performing anywhere near their potential range of abilities. Contributing to this problem is the fact that with conventional controls, vectored-thrust and rotary-wing flight are inherently unstable. Roscoe and his colleagues (Bergman, Sivier, and Roscoe, 1973; Roscoe and Kraus, 1973; Roscoe and Bergman, 1980) suggest that, for these craft to approach their potential, control systems are needed that provide stability and also direct maneuvering performance control. Momiyama (1979) and Ringland and his associates (1977) also suggest that more automation is needed and that improved displays alone cannot completely solve these problems.

Contributing to the failure of helicopters and VTOLs to perform optimally is the fact that current instrumentation (both controls and displays) results in high levels of pilot workload. Automation will partially reduce this load, especially during critical mission phases, but other control deficiencies must also be corrected to reduce pilot workload to an acceptable level during all thrust-borne flight. Some possible approaches to this are better display-control synthesis (Roscoe, 1980), a better understanding of how pilots allocate attention (Roscoe and Kraus, 1973; Derrick, 1981), and an application of the principles of flight performance control to VTOL and helicopter system design (Roscoe and Bergman, 1980).

Displays

Although better design and integration of controls is important in any attempt to approach optimum performance of helicopters and other VTOL craft, a major thrust in such an attempt lies in the improvement of cockpit displays. Although basic ideas like display integration have been strongly recommended for years, manufacturers and users of helicopters have been slow to adopt these suggestions. Indeed, because of this, Momiyama (1979) reiterates that no improvement in performance abilities occurred between 1973 and 1978. Displays currently in use, such as those discussed in detail by Ellis and Fahy (1981), still fall short of providing pilots with necessary information in an integrated and manageable fashion.

Frank (1979) notes that displays vary greatly from actual military specifications. Gold and Walchli (undated) report that conventional displays are cluttered with too much symbology. Keane and Milleli reported on the success of the Integrated Trajectory Error Display in 1971, but such a display has not yet been adopted and modified for VTOLs. Two AGARD reports (NATO, 1972a, 1972b) specify display requirements and the nature of control-display tradeoffs in VTOL systems. Guidelines for study to determine the information requirements for manual control are given, and areas for future research and development are recommended.

One glaring deficiency in displays for helicopter and VTOL operations is a lack of presentation of other traffic nearby, especially for shipboard and remote area takeoffs and landings when many vehicles are operating in the same area. Hart and Loomis (1980) and Palmer, Jago, Baty, and O'Connor (1980) describe several advantages of the cockpit display of traffic information (CDTI) for aircraft, including the increased traffic flow that CDTI makes possible under IFR conditions. Although CDTI displays are still under development and candidate procedures are being studied (Systems Control, Inc., 1980), it appears that CDTI may provide major benefits in operating VTOLs and helicopters.

IFR and Accidents

One of the more evident problems with helicopters and VTOLs today is their accident proneness. As noted in the Executive Summary, a former Navy helicopter flight test director (William O. Wirt, personal communication) analyzed 700 helicopter crashes with the surface in a 20-year period, 60 percent of which he attributed to display deficiencies. Scolatti (1971) discusses the difficulty that thrust-borne craft experience under IFR conditions. This is borne out by McMuller (1976) who reports that shipboard landings under IFR conditions are made only when visibility and ceiling are substantially above zero.

Yet AGARD participants (NATO, 1972a, 1972b) and Holzhauser, Morello, Innis, and Patton (1972) believe that helicopters and other VTOLs should be able to operate under adverse weather conditions. Currently, this is prevented only by poor control and display instrumentation. Both Scolatti and the NATO advisory group contend that safe IFR operations require ground- and airmass-referenced displays, increased field of view, better display integration, and attitude stabilization through automation.

INFORMATION REQUIREMENTS

The Information Requirements Puzzle

It might well seem that the delineation of a set of pilot information requirements would be a straightforward, albeit time consuming, task. Following the traditional systems engineering approach, one would simply analyze the pilot's task and list his information requirements. As Hennessy et al. (1980) discuss, this approach has been taken many times with little demonstrable practical result. As they explain, typically the constructer of such a list is forced to conclude that there is no intelligent way to leap from it to the definition of a set of environmental sources of the requisite information. Similarly, as Carel (1965) argues, such lists of pilot information requirements are useless because there is no rational link between them and how information requirements are encoded by pilots.

This position receives considerable further support from Lintern and Roscoe (1980). In an exposition of visual cue augmentation their thesis is that one may profitably (economically and scientifically) use a visual simulator to provide learning experiences different from those found in contact flight training. They describe several studies of visual simulation that can be seen to bear on our current point. Specifically, they discuss a triad of early aviation studies (Brown, Matheny, and Flexman, 1950; Payne, Dougherty, Hasler, Skeen, Brown, and Williams, 1954; Creelman, 1955) involving rudimentary visual simulators that provided the student pilot not much more than a crude dynamic perspective view of the runway he was attempting to "land" on. Notwithstanding the primitive nature of the visual simulation, Creelman found that it was operationally effective.

As behavioral research often does, these and related experiments uncovered new and challenging research problems. Payne et al. (1954) and Hasbrook (1975) independently noted that even experienced pilots are unsure of what visual cues they use when landing. The slippery nature of such cues is evident from the work or James and Eleanor Gibson. Gibson, Olum, and Rosenblatt (1955) suggested that the center of apparent expansion of the visual field is a cue to approach path tracking. Later Gibson (1966) found support for the idea that climb/sink rate is used by pilots during roundout and flare. Walk and Gibson (1961) also inquired as to what cues are used in this maneuver and concluded that the density of ground texture and angular velocity were important.

However, Johnston, White, and Cumming (1973) showed that the center of apparent expansion of the visual field and the other cues mentioned are extremely difficult to discriminate and, in fact, cannot be discriminated with anything like the precision that would be required to serve as the basis for controlling an approach to a landing. Johnston and his associates concluded that the most easily discriminated visual cue for controlling the glide angle is the distance of the aimpoint below the horizon. To land on the aimpoint, this so-called "h-distance" should be held constant, a technique advanced by none less than Wolfgang Langewiesche in 1944 and given scientific status a

few years later by John Bell (1951) and by Thomas Payne, Alexander Williams, et al. (1954) at the University of Illinois.

Unconventional Displays

What is really needed here? Hennessy et al. (1980) state that the issue involves two determinations: (a) "What are the essential information affordance characteristics of the natural visual environment that must be present in a simulated scene?" and (b) "How should the sources of information be represented?" (p. 51). Hennessy elaborates on this general theme in a recent report dealing with so-called unconventional displays (Hennessy, Lintern, and Collyer, 1981). This report begins with a discussion of visual image alteration (VIA), a technique that changes a computer image generation (CIG) data base to produce a simulated scene that is less "natural" than the contact scene viewed by a pilot.

The most common use of VIA enhancement is to compensate for CIG attributes that would inhibit or prevent learning. For example, a researcher might overlay the simulator's CRT screen with a checkerboard pattern to provide visible texture for a pilot receiving low-level flight training. VIA enhancement can also be used to help pilots interpret scenes encountered during contact flight, much as Lintern (1980) used visual cue augmentation to assist pilots' simulator landing performances. VIA degradation may also be called for at times, especially to save money and reduce the potential confusion of a complex scene; Lintern used skeletal figures as a strategy to remove extraneous stimuli from some of his experimental displays.

As their thesis, Hennessy et al. (1981) propose that unconventional displays can be used to optimize the teaching of certain components of a complex task, rather than teaching the entire task. Further, they indicate that such displays may not resemble real-world scenes at all (cf. Lintern and Roscoe, 1980, p. 230). Additionally, they distinguish between two categories of learning that must occur in pilot training but not necessarily simultaneously: perceptual learning and control-skill learning. They also argue that to use the same display to teach both may very well be inefficient because they can and are learned separately and at different rates.

To support their position, they reported a transfer-of-training experiment in which uncoventional displays (an Outside-In view of the pilot's own craft and an Instruments-Only display) were compared to Narrow and Wide Field of View (FOV) conventional CIG scenes. Details aside, they concluded that pretraining with unconventional displays speeded subsequent transition to conventional displays as indicated by steep, negatively decelerated transfer error curves. These results were consistent with the hypothesis that control skills can be learned rapidly with displays that induce correct responses quickly and that a rapid increase in performance during transfer indicates that, once the control skills are acquired, perceptual learning comes easily and quickly.

They end with the caveat that to determine conclusively whether

unconventional displays are advantageous for training, more complex flight-related tasks should be used. As examples, they enumerated the following: (a) aerobatics that are precursors to air combat maneuvering training, (b) helicopter landings on the decks of air-capable ships, and (c) air-to-ground attack or nap-of-the-earth flight regimes. It must be remembered that Hennessy et al. are not advocating just any type of unconventional presentation but rather one conducive to correct control responses.

The foregoing has significance for our research endeavor in several ways. First, we are now fully and sufficiently warned about the information requirements morass. Second, the displays that we propose can also be called unconventional in the same sense, and the potential worth of such displays demonstrated by Hennessy and his associates (1981) is encouraging. Last, and most importantly, we are prompted to state the next logical premise: If unconventional displays of this type can benefit pilot training, they may likely aid pilots during instrument flight.

Position, Rate, and Acceleration

If one embraces the unconventional display as a human factors research tool and potential flight control aid, one must still consider the question of what these "stick figure skeletons" will portray or equivalently what dynamics of the aircraft will be used to drive such a display for use in an aircraft capable of some independent motion in all six degrees of freedom. For a pilot to control this type of aircraft, he must receive information about its current and future position, rate, and acceleration in these several dimensions. Because the pilot is primarily interested in controlling his craft's position during low-speed flight, this information is more important to him during this phase than during en route or even weapon delivery phases.

A study by Kaul, Collyer, and Lintern (1980) dramatically demonstrated the importance of rate information in controlling fixed-wing aircraft. In a FLOLS simulation, they provided CTOL pilots with rate of descent information and found that this information substantially increased carrier landing performance over that obtained without such indications. The usefulness of rate of descent information was similarly emphasized in an earlier series of experiments that also involved simulated carrier landings (Pitrella, Prosin, Kelley, and Wulfeck, 1971; Prosin, Burger, and Wulfeck, 1972; Wulfeck et al., 1973). Bode, Kendricks, and Kane (1979), Dukes (1971), Hemingway (1978), Keane and Milelli (1971), McElreath (1979), Momiyama (1979), NATO (1972a, 1972b), and Nethaway (1971) have also examined the usefulness of rate information.

Attitude and position stabilization, particularly avoiding sideslip during hover or transition, are acknowledged to present an insidious problem to VTOL pilots. The effective presentation of information concerning the aircraft's translational as well as rotational accelerations would help ameliorate this problem (Johnson and Roscoe, 1972; Jensen, 1979; Roscoe, Johnson, and Williges, 1980). An additional feature, providing an ideal solution, would be the adoption of inertially

referenced control augmentation to provide positional stability as well as attitude stability. Translational accelerations would be automatically nulled unless called for by pilot control inputs, thereby fully compensating for airmass movement and turbulence.

Unique Information Requirements

Earlier a distinction was made between information in an abstract sense and the sources or perceptual cues from which such information may be derived. A specific example of the former might be the basic question of present energy availability. Because VTOLs are entirely thrust-borne during hover and largely during transition, an integrated indication of available thrust, power, or engine performance would be especially beneficial. Absence of such information, as has been the case, can adversely affect the pilot's already extreme workload and safety. An integrated presentation of engine performance would also benefit helicopter pilots who must now induce it by simultaneously monitoring three or more displays.

IMPLEMENTATION

Our approach to these problems is being implemented on the Behavioral Engineering Laboratory's versatile PDP 11/23-based MicroGraphic Simulation System that also includes a secondary ADAC System 1000 computer, a Hewlett-Packard 1350A Graphics Translator and 1311A Display, and two 512 x 512 dot-matrix plasma-panel displays. This system can be used either with a Frasca helicopter simulator or in conjunction with BEL's Enterprise Operator's Console (also known as Capt. Kirk's chair) to simulate a generic control-configured VTOL vehicle as described in Appendix A. In either case the operator can be presented with two flat display surfaces on which forward-looking and downward-looking views are generated.

Our experimental approach to the implementation of realistic requirements for vehicles of the next decade and beyond involves manipulation of vehicle performance variables and control relations as well as dynamic and configurational display variables. The basic problem is, as it always has been, the practical difficulty of unambiguously displaying and controlling six independent dimensions of position and attitude (three each) relative to both the airmass and surface topography. To reduce the problem to a point of tractability, we have assumed that within our target time frame, engineering technology can provide precise sensors of any information needed and precisely vectored thrust over wide ranges in any direction.

As stated earlier, given these liberating degrees of freedom, we are experimentally exploring the display of flight information and the control of thrust-borne aircraft without the restrictions traditionally assumed by aircraft control and display system designers. Although helicopters may continue to be designed with more limited maneuvering performance than control-configured VTOLs, the control and display principles derived from this approach should be applicable to either type of vehicle.

Contact Analog Displays

In configuring a contact analog vertical situation display (VSD), several tradeoffs always have to be made, whether or not the designer is aware of the nature of the alternatives and the consequences of the choices that are eventually selected. The first tradeoff, from which many others stem, is the choice of the physical size of the display itself, or more strictly, the visual angles subtended by the boundaries of the display, whether presented head-up or head-down or as a virtual image generated by a helmet-mounted device that moves with the head.

In any of these cases there is a difficult tradeoff between the desire to present the largest possible outside angular representation (field of view) without increasing display size and the biased position judgments in ground-referenced flight that result from image compression (Roscoe, Hasler, and Dougherty, 1966; Roscoe, 1982). This eternal conflict leads to other design tradeoffs that may or may not be considered by the display designer. These include providing variable

display magnification (depending on task requirements), displacing the pilot's point of view to a position outside and behind the airplane (presumably a variable distance), and even the possibility of radically unconventional cockpit configurations.

Cockpit configuration. Considering these tradeoffs in the reverse order, we do not find it unreasonable to assume that within this decade sensor and display technology will support ground-referenced flight operations without any direct outside visibility. To make this possible it will be necessary, first, to develop a scanning or other imaging sensor with sufficient cloud-penetrating capability for use in conjunction with high-resolution TV and optical image intensifying systems; second, to make relatively modest advances in current flat-panel display technology; and finally, to position the pilot in a fat part of the airplane so that a faceted arrangement of flat-panel displays can provide whatever outside coverage may be required by the missions of the particular helicopter or VTOL craft.

On these display facets surrounding the pilot can be superposed both the sensor-generated imagery and the computer-generated contact analog with its imbedded command guidance and flight path prediction symbology, all beyond the wildest dreams of the early proponents of these original ANIP (Army-Navy Instrumentation Program) concepts. Ironically, what is being given up is any direct view of the outside world, which the ANIP proponents considered the ultimate flight display. However, the proposed applications are intended to support zero-visibility ground-referenced flight operations that are currently impossible, and realistically, if pilots are to perform them effectively and safely when the weather is bad, they need to perform them routinely in the same way when it is good.

Displaced viewpoint. In the immediately preceding discussion it was implicit, for the purpose of exposition, that the center of a partial spherical arrangement of display facets is the pilot's head. Furthermore, it was implicit that the sensor- and computer-generated images bear a point-to-point radial correspondence to the picture-plane projections of their outside-world counterparts (when they exist). Though probably desirable, neither of these conditions is necessarily the case, and each is potentially subject to tradeoff compromises. As mentioned earlier, it would be possible, at least in the case of the computer-generated symbology, to displace the pilot's point of view to a position some variable distance behind the airplane.

While this may seem a strange thing to do, some of its consequences might be advantageous in helicopter control. One such concept has been advanced by CDR Kent Hull of ONR (Personal communication). Displacing the pilot's vantage point abaft the helicopter has the effect of including more of the outside world above, below, and to either side of the helicopter within a forward-looking display of relatively modest size. Computer-generated symbology can indicate the downward projection of the helicopter's position onto the land or sea surface below, as well as its desired ground track ahead and its projected flight path predicted from current movement and control inputs. By displacing the pilot's vantage point in this way, a single display can

serve some of the functions of a downward-looking display as well as those of a forward-looking display.

Followers of the history of pictorial display concepts may notice a superficial similarity between the display just described and the illustrations that appeared in the second issue of the very first volume of the journal Human Factors (Fogel, 1959). The apparent similarity is indeed superficial, because the kinalog concept originally advanced by Fogel in 1957 and the displaced viewpoint idea advanced by Hull in 1981 are intended to solve quite different problems, respectively, control-display motion compatibility and spatial and topographic orientation. Hull's concept includes a computer-generated surface grid whose dynamic behavior provides indications of both coordinated and unbalanced helicopter motions near the surface and indications of ground speed, altitude, and vertical speed.

Once the notion of displacing the pilot's vantage point from the cockpit of the airplane is considered, a host of new tradeoffs must be made. The pilot's vantage point might be fixed in space as when flying a radio-controlled model or drone that is always within visual range. For example, the pilot's vantage point might be fixed, say, at a position two nautical miles abaft a carrier deck on the projection of the desired final approach path. Then the pilot could manuever his vehicle into the field of view and see it approach the unchanging landing deck from an unchanging viewpoint. The only perspective cue to distance from the carrier would be the size relation between the shrinking vehicle symbol and the unchanging deck.

Evidently the objections to any such arrangement are so numerous that fixed-in-space vantage points (or ones fixed relative to a moving goal) warrant no serious consideration. Instead we will consider only alternatives involving displacement from the aircraft itself. For example, the vantage point of the perspective view might be 1000 yards behind the vehicle on its fore-aft body axis. The aircraft is visible in the center of the screen along with the projection below it of its position on the surface, which in turn can be related to any desired track on the surface.

However, if the projection of the aircraft's position on the surface is to be visible at high altitudes, then the vantage point must be moved farther abaft until the evident defects of the fixed-in-space vantage point become defects of this viewing mode as well. When the aircraft is about to land on the deck, the vantage point is still some distance away, and the difference between the scene for the pilot and the observer at the vantage point becomes very large. However, the extra information provided by the projected position on the surface makes it possible to tell when the vehicle is approaching and then is over the landing deck.

Again, in some mission phases, such as en route cruise, the compact representation of the three-dimensional scene not only includes the aircraft's projected current position on the surface but also a perspective view of the locations of such items as navigation waypoints, targets, ground defenses, and desired track over the surface. Further-

more, the low-altitude problems may be solved by a rule that the vantage point is separated from the vehicle by a distance proportional to altitude or to the vehicle's separation from a specific goal object.

Variable magnification. In the preceding discussion of the displaced viewpoint or vantage point, it was implicit that the projection of the scene on the display is otherwise undistorted. Of course it is also possible, without displacing the pilot's vantage point from the cockpit, to expand his outside field of view by compressing or minifying its representation on a display of limited size. The effect, which may be likened to viewing the projection from a "fish eye" lens, was studied at the University of Illinois in an airplane equipped with a projection periscope with variable magnification (Roscoe, 1951; Roscoe et al., 1966).

Compressing the outside view proved advantageous for orientation, navigation, and aircraft attitude, heading, and altitude control, but it also proved unacceptable for ground-referenced maneuvers such as landing. To obtain veridical judgments of position relative to the ground and surface objects an image magnification of about 25 percent was required by most pilots. So while variable image magnification and minification can serve useful purposes, this approach does not offer a solution to the need for a large field of view when flying by reference to surface objects. Some combination of flat-panel displays surrounding the pilot and a downward-looking horizontal situation display for geographic orientation and navigation planning appears necessary.

Guidance and Prediction

Whatever the vantage point and magnificaton for a contact analog scene may be, goal symbols, such as a highway in the sky or a desired ground track or a fly to point, can be added as well as predictions of future vehicle position. The highway in the sky could consist of T-bars defining the desired flight path as well as its projection onto the surface. An important provision is that these symbols not behave like real obstacles but disappear from the screen before the vehicle reaches them. (Pilots don't like to fly into computer-generated buildings, towers, or telephone poles.)

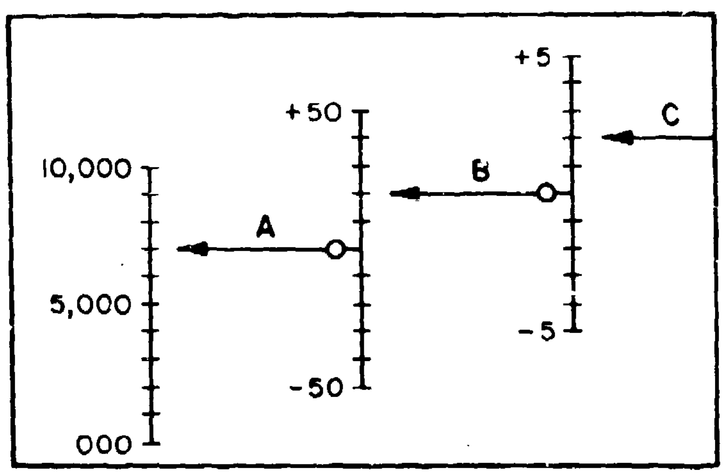
One way to do this is to display a moving circle or other symbol on the goal path some set time ahead of the location on the goal path closest to the present vehicle location. When this symbol arrives at a T-bar, that T-bar disappears, and another appears beyond the most distant one already present. Alternatively, two bars on a pole or a rectangular frame on a pole could be used to specify successive windows to be flown through. The interval between these symbols could be set to a standard distance or a standard time for goal speeds.

What is really needed to be compared with the goal posts out in front somewhere is a symbol that predicts where the vehicle will be some time in the future. This is the true predictor symbol. A series of such symbols could be drawn for different times in the future, each based on extrapolating the full knowledge of the vehicle's present

behavior to the specified fixed time in the future. It is also possible to display a series of predictors using the same fixed time in the future, but applying successively higher orders of prediction to each succeeding predictor. The relative effectiveness of the alternative algorithms needs to be explored further (Jensen, 1979).

The successively higher-order predictors are similar to another predictor concept based on a completely different idea (Roscoe, 1980). This involves using symbols to display a series of variables each with its own scale factor and using the previous symbol in the series as the reference for the next variable's scale. As an example, consider the series of variables: altitude, rate of climb, and vertical acceleration. The display of altitude would position one symbol, say, along a scale from 0 to 10,000 meters, and a second symbol would indicate the rate of climb by its displacement above or below the first symbol on any scale chosen for display of this variable. Finally, a third symbol would display vertical acceleration by its displacement from the second symbol using another arbitrary scale factor.

Given:



Indicating A at 6945 m, B at 21 m/s, and C at 2 m/s^2.

Pointer B is a true predictor of altitude a time $\underline{tb}$ in the future such that:

$$21\underline{tb} + 6945 = 8880$$ (the alignment of pointer B with the altitude scale)

so $$\underline{tb} = (8880 - 6945)/21 = 92.1 \text{ seconds},$$

which holds for any position of pointer A and B.

But pointer C is predicting:

$$2\underline{tc}^2/2 + 21\underline{tc} + 6945 = 12050$$

so $$\underline{tc}^2 + 21\underline{tc} - 5105 = 0$$

and $$\underline{tc} = 61.7 \text{ seconds}.$$

While if B drops to 10 m/s leaving C unchanged and thus indicating 2.5 m/s,

$$2.5\underline{tc}^2/2 + 10\underline{tc} + 6945 = 12050$$

so $$1.25\underline{tc}^2 + 10\underline{tc} - 5105 = 0$$

and $$\underline{tc} = 53.3 \text{ seconds.}$$

Because the prediction time for C depends on the level of variable B, C is not a true predictor of altitude at any fixed future time. Instead it should be referred to as a precursor or advanced warning display, since knowledge of present rate of climb and vertical acceleration provide equivocal indications of what will happen to altitude later on. Nevertheless, appropriate selection of the arbitrary scale factors for the successively higher-order terms could result in improved stability of manual control, as has been found with other frequency-separated displays (Beringer, Williges, and Roscoe, 1975; Jensen, 1979).

The Horizontal Situation Display

A wide-angle contact analog display with embedded guidance and prediction symbology serves all mission functions involving spatial and topographical orientation in translational flight, including air combat maneuvering and ground attack. With an optional displaced vantage point, the contact analog can also serve some mission functions involving geographical orientation, including terminal area navigation and short-range en route navigation. However, it cannot be expected to serve all functions equally well, and there are some functions that it cannot serve in even a minimally acceptable manner. Specifically, we cannot expect a contact analog to serve alone in the performance of maneuvers that are very difficult or impossible to perform with contact visibility.

Obvious examples of functions not adequately supported by contact visibility are long-range (beyond line-of-sight) navigation over water and even short-range navigation over water when no surface objects are visible and no shore objects of known location can be identified. Although computer guidance is readily embedded in a contact analog, it is not evident how a pilot would set a desired flight path or navigation plan into a computer by reference to this type of display, and because of its line-of-sight range, the planning function itself is not well supported. Clearly a map-type horizontal situation display (HSD) is needed no matter how capable the VSD.

Also, despite the pilot's legal requirement to "see and avoid" other traffic in clear weather, this doctrine is not realistic. Both the detection of other traffic and the extrapolation of potentially conflicting flight paths for collision avoidance require instrumental means. Currently there is an urgent program to implement the cockpit display of traffic information (CDTI). Practical limitations on the fields of view of vertical situation displays prohibit omnidirectional coverage, and for this and other reasons it is properly assumed that CDTI will be embedded in a horizontal display with altitude coding.

However, human perceptual ability to extrapolate potential conflicting flight paths is not well understood and needs study.

Less obvious perhaps is the fact that helicopter and VTOL operations at very low speeds near the surface are extremely difficult and hazardous even with the best of visibility, particularly if they require precise horizontal positioning. Sonar dipping, landing on small decks in rough seas, and the transitions between thrust-borne and aerodynamic flight present serious training and safety problems. Since these maneuvers are difficult in clear daylight and currently impossible under instrument meteorological conditions, we cannot expect them to be performed easily and safely solely by reference to a contact analog, even one with guidance and prediction features.

Little attention has been given to the analysis of why these ground-referenced maneuvers are so difficult except to point out the obvious fact that conventional helicopters and VTOLs are terribly unstable in thrust-borne flight. Occasionally it is noted that maintaining position is difficult because it is difficult to detect and judge drift visually and translational rate and acceleration information is not displayed. Nowhere have we found an explicit statement that the focus of difficulty has shifted from the precise control of vertical situation variables (in high-speed translational flight) to the precise control of horizontal situation variables (in vertical flight).

Clearly stability and control augmentation are needed in these vehicles (see Appendix A), but even with stable rate control of inertial position (fully compensated for airmass movement) an effective presentation of precise horizontal position, rates, and accelerations is needed for maneuvering control. Although map-type HSDs are used in ASW helicopters, they are designed primarily for tactical coordination and not for precise aircraft translational control and station keeping by the pilot. A very large scale HSD showing horizontal and vertical rates and accelerations as well as position and vertical clearance should be more effective than any type of VSD for precise station capture and keeping.

In aerodynamic translational flight VSDs allow precise steering control in the up-down and left-right directions, but they offer little help in controlling forward rates and accelerations. As a consequence we have dedicated airspeed indicators. So in thrust-borne vertical flight, in which precise steering is required in the fore-aft and left-right rather than the up-down and left-right directions, a downward-looking display, or plan view, is needed. The advantages of a special HSD mode for steering control in vertical flight become evident once this alternative is considered; what is surprising is that it was not proposed and implemented long ago.

Suppose a pilot must maintain a precise hovering altitude over water on a clear, calm, dark night solely by reference to a distinct horizon defined by lighted homes along the coast. Clearly his task would be impossible; there is simply no information in this night contact scene to tell him where he is relative to his command altitude

and whether to go up or down to correct his momentary vertical errors. But suppose there is a pole with electroluminescent scale markings sticking up out of the sea between the pilot and the coast; immediately the missing information is provided.

With the just-invented Excalibur display, the pilot can read altitude by the position of the horizon against the vertical scale. Notice that even if the pole were a long distance away, it would still be helpful, so long as the pilot knew the length of the scale and could thereby judge the proportion below the horizon. And of course, if the pole were very near, he could read his altitude to some fraction of an inch. Further, if his command altitude were indicated on the scale, and the markings indicated deviations above and below that datum, error indications suitable for tracking control would be supplied directly.

We are proposing embedding artificial objects in the VSD in the form of highway-in-the-sky T-bars or other symbols. Flying such a highway in the vertical contact analog display will give an indication of small lateral and vertical errors, but not of fore-aft ones. The necessary precision in this depth dimension is lost in the picture-plane perspective computation. The natural place for a precise presentaton of fore and aft errors is in the horizontal plane, normal to the VSD, in which case the collapsed dimension is altitude. The use of an appropriately configured HSD for controlling lateral and fore and aft position is analogous to the use of a VSD for lateral and vertical tracking.

<u>HSD Design Variables</u>

Traditionally HSDs in CTOL aircraft have differed from VSDs in a number of fundamental ways, most notably: motion relationships, scale factor options, and topographic detail.

<u>Motion relationships</u>. VSDs, at least those of the contact analog variety, are inherently inside-out presentations (analogous to a port-hole). Elements representing outside-world counterpart objects are presented in an aircraft coordinate reference system. Consequently what portions of the outside world are included in the display's field of view and their angular orientation depend on the aircraft's flight attitude which may change from moment to moment. Thus the scene can and often does change rapidly and in the opposite directions to those of the aircraft's angular rotations in pitch, roll, and yaw.

In contrast, HSDs traditionally (though not necessarily) are stabilized against changes in aircraft pitch and roll and change their orientation only in response to changes in heading and of course to translation in the horizontal plane. These latter motions are the pilot's primary concerns in planning and controlling the aircraft's geographical position, commonly referred to as navigating. Perhaps because map displays are pitch and roll stabilized, much attention has been given to the various direction of motion relationships that are possible in the horizontal plane. Experience and experimentation show that different relationships are best for different purposes.

Consider the following four basic alternatives: Either the aircraft or the map can rotate and/or translate. These issues were first debated and studied experimentally in the late 1940s and early 1950s (Williams and Roscoe, 1949; Roscoe, Smith, Johnson, Dittman, and Williams, 1950; Payne, 1952). Somewhere along the way someone assigned the letters A, B, C, and D to the following arrangements:

A--Aircraft rotates and translates over a fixed map, normally but not necessarily North up or forward on the display.

B--Aircraft rotates to indicate heading relative to a fixed compass rose, but map translates in the direction opposite to the aircraft's heading.

C--Map rotates and translates relative to a fixed aircraft symbol heading up or forward on the display and usually, but not necessarily, in the center of the display.

D--Map rotates to indicate heading relative to an aircraft symbol that points up or forward on the display, but the aircraft symbol translates ever upward or forward (no one has seriously proposed using this arrangement).

In practice only the A and C arrangements are used in CTOL aircraft (with a single notable exception: the British Deccalog System involves a longitudinally moving strip-chart with a laterally moving stylus that results in a hybrid arrangement most nearly of the B type). The basic A and C arrangements each has its advantages and disadvantages for different purposes and, strangely enough, for different pilots, about half of whom are "map turners" and half "North uppers." So the parsimonious solution is to provide a switch that allows each pilot to choose the arrangement that suits him best for each mission function.

For everyone, including map-turners, the fixed map with North up (Type A) is the best arrangement for navigation planning, and for many it is the preferred mode for en route flying. However, the Type A display presents difficulties when a southerly course is being flown (heading down the display), in which case making minor heading corrections can be confusing. The Type C display, on the other hand, maintains a directional congruence with outside referents that is advantageous in maintaining topographic orientation, but because it always rotates in the direction opposite to the direction of turn, momentary control reversals occasionally occur. However, these can be virtually eliminated by incorporating a fast-acting flight path predictor.

<u>Scale factors</u>. As with motion relations, different map scale factors are needed for different functions. With the rapid advances in computing technology there is a temptation to adjust map scale continuously as a function of altitude (above the surface) or ground speed, or some combination thereof. However, this has not worked out well when tried. The effectiveness of map displays for instant geographic and topographic orientation seems to depend a great deal on the fact that their symbolic elements representing fixed objects or locations do not

change relative positions dynamically as do the pictorial elements of a contact analog display.

Still there is a need for different maps for different purposes, varying not only in area of coverage (large coverage at a small scale to limited coverage at a much expanded scale) but also in content (so that no one map becomes too cluttered with information needed at other times). Generally it has proved most effective to have the pilot select map scales manually, but in the case of content, the pilot should not have to select items individually; subsets of cartographic items can usually be associated with mission phases and, within phases, with operating modes.

Topographic detail. Because VSDs are primarily associated with precise steering in azimuth and elevation during translational flight, topographic detail is normally limited to such items as airports, carriers, ships with small landing decks, tactical target locations, and possibly surface buoys or other markers. In operations over land, terrain elevations may be shown in perspective contours suitable for terrain following or avoidance, and these computer-animated representations may be augmented by sensor imagery revealing the locations of specific objects such as bridges, buildings, tanks (of either kind), or other items of tactical importance.

Map displays, on the other hand, can contain a wealth of topographic information limited only by available intelligence and the need to avoid clutter and confusion. Furthermore, map items and other traffic in the vicinity can be identified by various abstract symbols and by specific numerical and verbal identifiers that would be totally impractical with dynamic pictorial vertical situation displays. For some purposes pictures are more effective than abstract symbols, but the converse can also be true; it is far easier to recognize and remember a specific number between 1 and 9 than it is to pick a stickup man out of a police lineup.

Horizontal Displays for Vertical Flight

For precise translational control and position keeping in vertical flight, a horizontal situation display must present rate and acceleration indications not normally associated with map displays. In effect it becomes a flight control display rather than a navigation display. For this purpose a number of tried and true display principles and techniques can be applied effectively, including frequency separation (Roscoe, Johnson, and Williges, 1980) and vernier deviation indication (Roscoe, 1968), as well as command guidance and flight path prediction, mentioned earlier. Also, to support the level of control precision required, an extremely large scale (small area) not normally associated with map displays is required.

As mentioned previously, map-type HSDs used for planning and navigating are almost necessarily stabilized against pitch and roll motions of the aircraft, and such stabilization has proved desirable for terminal area maneuvering in CTOL aircraft. However, horizontal stabilization may or may not be desirable for the special purpose of vertical

flight control. The alternative of a downward-looking contact analog perspective projection has never been investigated experimentallly and evidently should be. Even a superficial analysis shows potentially important differences in direction-of-motion relations that could be helpful or harmful.

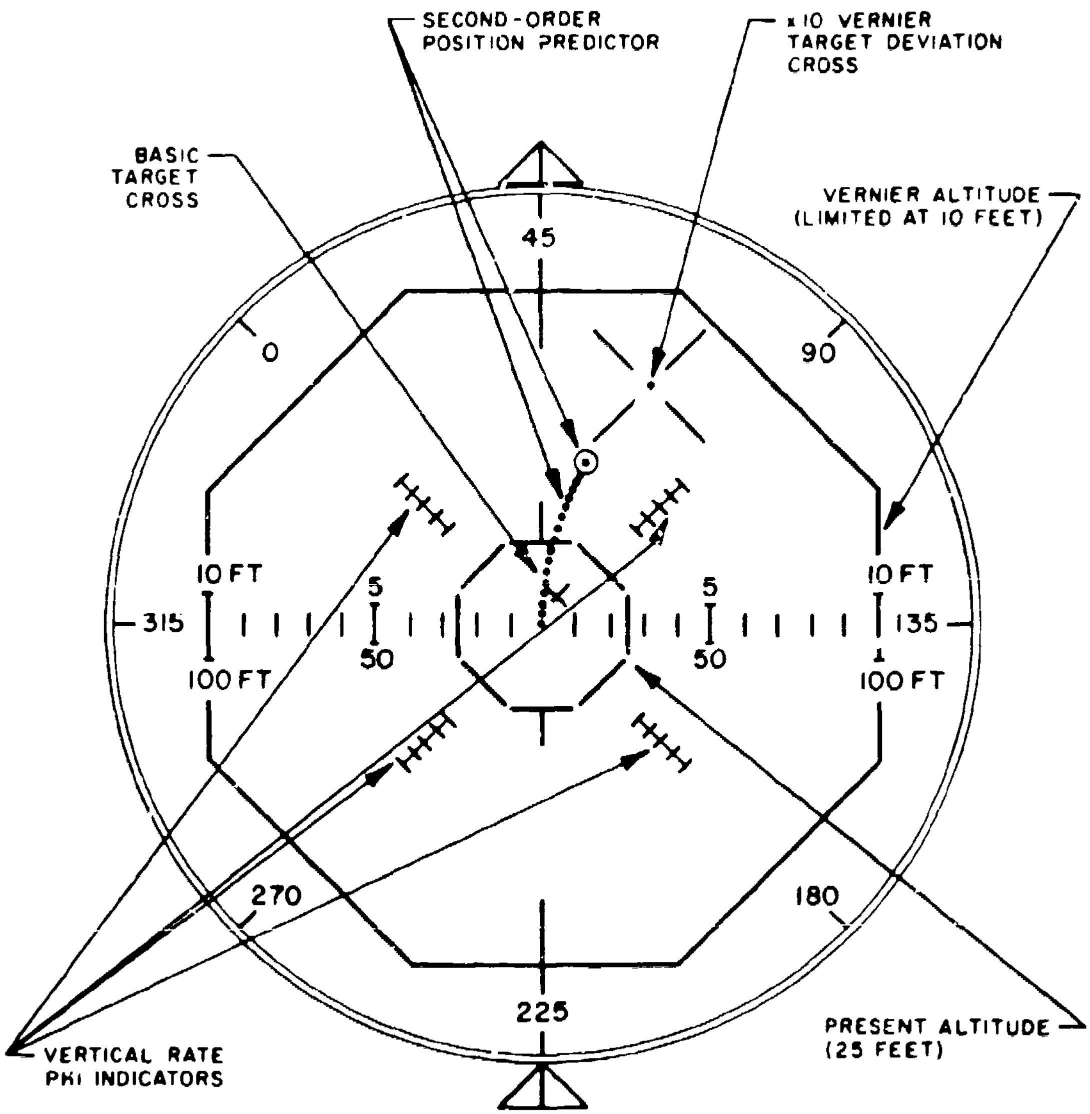
For example, the command surface position would move away from the display center to the left if the hovering aircraft drifts to the right <u>or</u> if it banks to the left. With conventional HSD stabilization, attitude changes are necessarily presented separately from position changes, so movement of the command position index away from the display center always indicates the development of a position error. Departures from neutral pitch and bank attitudes can be indicated directly on an HSD or, as in the example that follows, to help drive a position predictor used by the pilot either to hover over a point or to translate to another.

The display shown on the next page illustrates how these principles might be applied to a horizontal display suitable for hovering and translational control in vertical flight. Present position is always at the center, and the vehicle's heading is indicated by a rotating compass rose read against the fixed index at top center. Translational rates and accelerations along the longitudinal and lateral vehicle axes generate a second-order position predictor emanating from the vehicle's center position. Present altitude is indicated by the size of a hexagon read against a scale emanating laterally from center, and vertical rate by four small rate fields showing apparent motion (phi) in either direction (outward for up, inward for down).

Surface or near-surface objects or positions of tactical relevance are shown relative to the vehicle by variously coded symbology. In the illustration a single target position (goal) is indicated by a small cross (as if painted on the surface) and also by a larger cross that serves as a x10 vernier indication (magnification) of the target's relative displacement from the vehicle. The vehicle's future position predictor is scaled such that when the vernier target cross reaches the head of the predictor symbol, the pilot should reduce his translational rate to maintain the predictor head in the open center of the cross until directly over the goal.

The vernier deviation principle is also applied to the presentation of altitude above the surface. In the illustration, the altitude scale selected (by the pilot) represents a range from zero to 100 feet for the present-altitude index and a range from zero to 10 feet for the x10 vernier index, shown in saturation at its 10-foot limit (present altitude is 25 feet). If the pilot were to descend below 10 feet from the surface, the present-altitude index would disappear, and the vernier would shrink as the pilot descended to a touchdown. Throughout this maneuver the four vertical rate indicators would show an inward flow of apparent motion (possibly quickened by vertical acceleration).

In the preceding example, the goal altitude was the surface (zero). However, the goal or target altitude is selectable depending on mission requirements. For example, if the mission calls for main-


SECOND-ORDER
POSITION PREDICTOR
x10 VERNIER
TARGET DEVIATION
CROSS
BASIC
TARGET
CROSS
VERNIER ALTITUDE
(LIMITED AT 10 FEET)
45
0
90
10 FT
10 FT
5
5
315
135
50
50
100 FT
100 FT
270
180
225
VERTICAL RATE
PHI INDICATORS
PRESENT ALTITUDE
(25 FEET)

taining 25 feet, as shown, the size of the vernier target cross is scaled so that its tips just touch the edges of the altitude hexagon when centered over the desired position. Thus if the craft drops below the 25-foot goal altitude, the points of the cross protrude through the edges of the hexagon as a warning indication. Similarly, if the craft rises above its goal, the cross no longer fills the hexagon.

Although this horizontal display is basically an inside-out presentation mapped relative to aircraft heading, motion relationships are compatible with population stereotypes. The second-order flight position predictor is in effect a frequency-separated index that responds immediately to control inputs in the expected direction. Furthermore, the predictor symbol itself incorporates a rate-field indication of apparent motion in the direction of flight, and the flow of the vertical rate indicators constricts as the craft descends to a touchdown and dilates as it ascends. When the numerous dynamic variables have been experimentally optimized, this display should allow precise translational and vertical control in thrust-borne instrument flight.

APPENDIX A: GENERIC AIRCRAFT SIMULATION

To study the basic question of what displays a pilot should have to fly either a thrust-borne or aerodynamic control-configured VTOL vehicle, we have narrowed the design issues by making a number of reasonable simplifying assumptions, described in the text, and then defining a set of simulation characteristics consistent with those assumptions as follows:

First, simulate a model vehicle with mass and moments of inertia and lift and drag that vary with velocity. Such a model is described in A. Next, provide the operator with a specific set of six controls, as described in B. Next establish relationships between the controls and the behavior of the vehicle as described by three center-of-mass velocities and three attitude angles, for example, or any other set of descriptive variables. Three examples of this process are given in C. The set of controls described in B was motivated by the relationships to vehicle translational rates and attitude angles described first in C. The alternative sets of relationships in C may suggest modifications to the set of controls described in B.

The first two relationships described in C also reveal another complexity or opportunity. No one set of relationships should be expected to be best for all flight modes. A natural distinction might easily be made (a) between the hover mode in which aerodynamic lift and drag are of small consequence in any vehicle attitude because of the low velocities, but in which attitude is least flexible because of the limitations of thrust-vectoring angles, and (b) the aerodynamic flight mode in which full attitude angle ranges are possible in aerobatics, but the asymmetries of lift and drag forces reduce the range of velocity-vector to vehicle-axis angles.

Once different relationships between controls and vehicle behavior are allowed for different modes of operation, it is possible to consider changing the order of control also. In some cases a directly propotional angle of yaw control would be reasonable as an unburdening of the operator where a limited range of values is needed. At other times, a direct control of yaw rate would be much more useful in achieving a wide range of values. Thus in the hover mode the three translational-rate controls in the first C relationship might all be switched to position controls relative to some reference location. Or the three attitude-angle controls in the first C relationship could be switched to angle rates in aerodynamic flight to facilitate aerobatics.

Before any such shifting of relationships between manual inputs and vehicle responses is incorporated in an operational system, the means of doing so would have to protect the pilot against any possibility of mode equivocation. As a matter of good practice in display design, equivocation is avoided by providing unmistakably unique configurations for the different functional modes. Analogous safeguards can be provided in control design by associating unmistakably unique feedback dynamics, or feel, with the different control modes. Various means of force-displacement shaping are possible using spring-centered cams, viscous

damping, and isotonic devices that become isometric when shifting from one mode, say yaw-angle control, to yaw-rate control, for example.

Another narrowing of the general problem involves selecting the control-motion dynamics. Our selections based on the best established principles of manual control compatibility are illustrated in D. Finally, a set of displays is specified and simulated. Some of the alternatives are detailed in E.

A. The model vehicle will have mass and moments of inertia around three perpendicular axes and lift and drag as functions of airspeed on all three axes. It will be capable of producing positive and negative thrust forces on all three axes. However, the limits on most of the forces will be relatively small, with large values only for force in the forward-aft direction and the vertical direction to neutralize gravitation. There will be torques around all three axes generated by thrusters, so the vehicle acts like a spacecraft in its attitude-angle control. These torques will all be limited to relatively small values.

   The translational forces will all be applied to the center of mass, and the torques will be around the three vehicle axes. The model will be operated with inputs from the operator representing desired vehicle behaviors and solutions sought for the forces and torques required to achieve them. It may often happen that no solution exists within the vehicle limitations, in which case the best attainable behavior will be produced instead of the desired behavior.

   The model will accept an operator command to go to an autopilot mode that holds attitudes and velocities constant and ignores the control inputs. An alternate switch action will restore control authority. Questions can be investigated about various forms of limited operator-selectable control such as all three attitude angles frozen, or alternatively, "steady as she goes" translation rates, with the operator able to control the remaining vehicle freedoms. The model will include the possibility of motions between the airmass and the ground. This would allow simulation of winds and wind gust problems as well as landing deck motion of a ship.

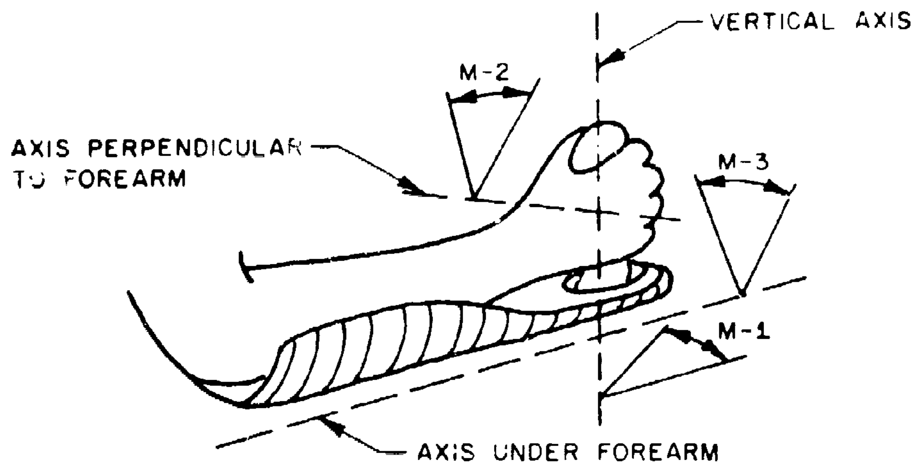
B. A manual flight controller operated by the right hand has six degrees of freedom of motion (M), three rotational (1-3) and three translational (4-6), as follows:

   M-1. The stick can rotate around an axis extending through the inside of the stick and running roughly vertical. Rotation in both directions will be countered by springs and viscously damped.

   M-2. The operator can also rotate the stick around an axis perpendicular to the one through the length of the stick extending roughly perpendicular to the forearm. This

axis intersects the first axis in the right-palm vicinity. This rotation also will be countered by springs in both directions and viscously damped.

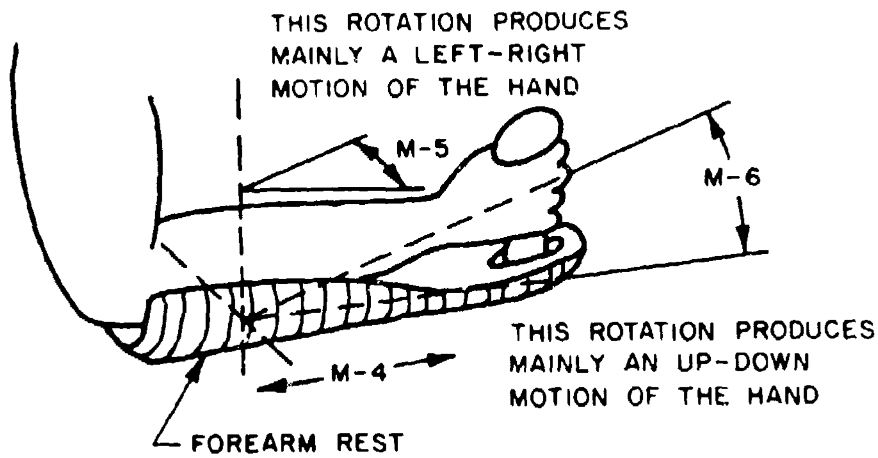
M-3. Next the entire hand and stick may revolve around an axis under and parallel to the forearm. This rotation is also resisted by springs in both directions and viscously damped.



M-4. The stick is mounted on a forearm rest that can be translated parallel to the forearm with spring-centering over a limited fore and aft range, beyond which it is viscously damped only with no spring restoring force.

M-5. The forearm rest can be pivoted around a pair of axes that intersect closer to the elbow than to the wrist in the vicinity of the center of gravity of the entire arm in its task posture. One axis is vertical with viscous damping and springs resisting rotation of the forearm around the axis in both directions. Although this motion is a rotation, the principal hand motion will be treated as a translation in what follows.

M-6. The other axis is horizontal, roughly perpendicular to the forearm, and in the same plane as the M-5 axis. Rotation around this axis is also viscously damped and resisted by springs in both directions. In what follows, this rotation is also considered principally a vertical hand translation, even though the position of this axis must be such that the weight of the hand and forearm is counterbalanced by the rest of the arm and shoulder to avoid involuntary inputs during high-G maneuvers.



C. Associate the rotation angles:

M-1 with the angular rotation of the azimuth of the aircraft's longitudinal axis. M-1 rotation controls heading change directly within a limited sector, beyond which increasing application of force elicits increasing angular rate;

M-2 with the angle of the aircraft's longitudinal axis measured perpendicularly from the local horizontal plane until the angle reaches some limit, beyond which increasing application of pressure elicits increasing angular rate; and

M-3 with the bank angle of the vehicle around the longitudinal axis until the angle reaches some limit, beyond which increasing application of pressure elicits increasing angular rate.

Associate the translation distances:

M-4 with the principal velocity component in either direction along the longitudinal axis of the aircraft;

M-5 with the incremental component of velocity in either direction perpendicular to the longitudinal axis in the horizontal plane;

M-6 with the incremental velocity component in either direction perpendicular to the longitudinal axis in the vertical plane.

Notice that the attitude and velocity control descriptions above can be in conflict. For example, suddenly rotating the stick in straight and level flight to force a 20-deg angle between the aircraft's longitudinal axis (its azimuth) and the horizontal velocity component (a 20-deg skid) means that the velocity controls inside the cockpit have also rotated 20 deg about a vertical axis relative to earth coordinates. A 20-deg angle has been introduced between the velocity controls and the corresponding momentary velocity components (soft groans from pilots).

One way to solve this inconsistency would be to think of the three attitude angle and/or angular rate controls as determining the pointing direction of a gimbaled turret in or on the aircraft whose translational velocities are controlled by the orthogonal M-4, M-5, and M-6 controls. The longitudinal velocity component, being regarded as principal, could constantly seek the longitudinal vehicle axis direction with a suitable and inevitable exponential lag. The incremental lateral velocity component and the incremental vertical component would be regarded as minor (reserved judgment by pilots).

One cause of trouble above is the difficulty of thinking of translational velocity in terms of three orthogonal components. The next example deals with total translational velocity in terms of its magnitude and two perpendicular rates of change of direction. This allows the operator to specify speed with the viscously damped M-4 control and then point or rotate the vector with the M-5 and M-6 controls (pilots resting more comfortably).

In this alternative association of control inputs and vehicle behavior in aerodynamic flight:

M-5 translation would set horizontal lateral rate of change of the velocity vector perpendicular to its continuously changing direction.

M-6 translation would set rate of change of the velocity vector perpendicular to its continuously changing vertical flight path angle (helicopter pilots are smiling).

In aerodynamic flight, no attitude control inputs (M-1, M-2, M-3) would be required, for the control system would automatically provide the most efficient coordinated flight attitudes to accomplish the commanded total velocity and vertical and horizontal rates of change of velocity. Attitude control inputs would be angles or angular rates relative to the coordinated attitude solutions and thus none would be required unless deceptive, uncoordinated flight attitudes were used tactically in aerodynamic flight (pilots see fun and games).

In the hover mode, the M-4 translation control reverts to the same spring-centered and viscously damped motion as M-5, since

the two directions of movement are equivalent given independent yaw angle (heading) and/or angular rate control with M-1. In this mode, the M-4 and M- 5 translational velocities will be heading-referenced and shown on a map display (loud cheers from map-turning pilots).

The two basic alternative control arrangements just described allow appreciable independence between flight attitudes and translational velocities. Either could satisfy all predictable maneuvering requirements for various missions but not necessarily in an optimum manner. The tradeoff between maneuvering freedom and pilot workload remains to be resolved experimentally for the various types of missions. Furthermore, the two arrangements described are based primarily on the requirements for ground-referenced missions and secondarily on air-to-air combat maneuvering. For the latter family of missions, a third arrangement, completely egocentric, might prove superior to either of the first two.

In this third alternative association of control inputs and vehicle behavior in aerodynamic flight:

M-1 rotation would control the rate of change of the direction of the velocity vector in the plane of the aircraft's "wings" (the horizontal plane for zero bank).

M-2 rotation would control the rate of change of the velocity vector perpendicular to the plane of the aircraft's wings.

M-3 rotation would control the rate of roll about the aircraft's longitudinal axis.

M-4 translation fore or aft would set the level of thrust fore or aft along the aircraft's longitudinal axis. Any remaining thrust available can be vectored laterally and/or vertically relative to the plane of the aircraft's wings as follows:

M-5 translation sets the incremental component of velocity in either direction along the aircraft's lateral axis, and

M-6 translation sets the incremental component of velocity in either direction along the aircraft's vertical axis, each within the limits of the vectorable thrust available.

Note that in this arrangement, M-4 controls thrust along the principal aircraft axis, not velocity, which will vary with the direction in which the aircraft's velocity vector is pointed with respect to gravity and with the drag forces imposed by the associated aircraft attitudes and any incremental velocities imposed by M-5 and/or M-6 inputs.

The potential advantages of this control arrangement for ACM missions are accompanied by serious disadvantages for the larger family of ground-referenced missions. With a purely ego-

centrically referenced control system (as in all conventional aircraft), there is no automatic inertial link to the geocentric reference system, not even by a common gravity reference. Thus to fly from directly over surface point A to directly over surface point B, the pilot must transform the ground-referenced task to an egocentric task, just as he now must do with conventional helicopters and VTOLs.

These transformations can be and routinely are made by pilots on clear days by reference to the visible horizon and surface plane for attitude control and visible and identifiable surface references for flight path and position control. In an analogous manner the required transformantions between geocentric and egocentric referents can be made using the types of VSD and HSD displays being studied in this program, but the pilot must still make the transformations moment to moment. With either of the first two alternative arrangements, aircraft control is inertially referenced as well as reasonably consistent with egocentric coordinates throughout normal maneuvering regimes.

D. Provide the following control element dynamics:

All control motions except M-4 are spring-centered and viscously damped on the presumption that releasing them should result in a neutral dynamic state of the vehicle. This is true of controls M-5 and M-6 for which the desired hands-off condition is straight flight with or without a fixed climb or descent and no lateral drift. The M-4 control, however, is spring-centered over a limited fore and aft range, beyond which it is only viscously damped so that a forward velocity component may be selected by the setting and left alone. This is most appropriate for the aerodynamic mode of flight.

In the hover mode, however, there is no operational distinction between the M-4 rate and the M-5 rate. The desired hands-off state is no rate in either horizontal direction, and consequently springs resist control motion in either direction. A reasonable dividing line between these two behaviors for the M-4 control might be at minimum aerodynamic flight velocity. For selected velocity below that required for aerodynamic flight, M-4 control force must be maintained by the pilot against the spring-centering. For selected velocity above this threshold, no sustained force application is required.

The attitude angle and/or angular rate controls are also spring-centered and viscously damped so that any deviation from the center represents a maneuver calling for operator attention and muscular effort. An autopilot mode could be incorporated that would take all or some control inputs and freeze them at current levels so the stick could be released until further operator override. The spring-centered control elements would all return to their neutral positions, and when their control authority was subsequently restored, their neutral states would call the vehicle back to coordinated straight flight at what-

ever longitudinal velocity was called for by M-4.

E. The operator is presented with two flat displays inside the cockpit. One is a horizontal situation or map display, and the other is a foward-looking outline perspective view of the exterior scene. On both are indices of desired position and/or guidelines or guideposts to the desired flight path and various possible symbolic configurations of predicted flight paths and limits of possible performance. Both views will also be used to provide the operator with cockpit displays of traffic information.

The displays can also be used to provide goal information for intermediate control orders in the manner MAJ Hector Acosta (USAF) calls SHOD (Stabilization of High-Order Dynamics). In this technique any pre-established maneuver will be displayed as goals for the operator to match by manipulation of control inputs. In the case of goals that cannot be met directly by a control setting, an intermediate goal appropriate to the maneuver will be displayed that can be matched with available control inputs at a lower order.

As an example, when a maneuver calls for a controlled variation of yaw using the M-1 control, the yaw goal will be displayed along with the actual yaw. Since the operator has direct control of yaw, no other orders of control would be needed. However, if the maneuver calls for a programmed variation in altitude, when the operator has control of the rate of climb or descent with M-6, the two goals, altitude and vertical rate, would both be displayed. Then the operator could directly match his M-6 input to the climb or descent rate goal and bias his climb or descent rate higher or lower to achieve a match of altitude to the goal.

F. As the experimental program progresses, and the initial questions concerning the selection of symbology and the various dynamic issues discussed in the text are resolved, the simulation will need to be upgraded by including either more display surfaces or a wide-angle projected TV display so that issues involving fields of view, displaced vantage points, image magnification and minification, and a wider range of mission functions can be studied with reasonable validity. To implement these expanded displays, an expanded computing capability will also be needed.

APPENDIX B: REFERENCES WITH SELECTED ANNOTATIONS

Alcock R. N., Atter, D., Robinson, S. J., and Vincent, R. P. Design and evaluation of a helicopter guidance aid. Proceedings of the AGARD Guidance and Control Panel Meeting, Konstanz, Germany. Neuilly-sur-Seine, France: North Atlantic Treaty Organization, 1971.

Alcock et al., in primarily an engineering report of a helicopter guidance aid, determined aircraft position with azimuth, elevation, and slant range. The use of slant range points out the importance of knowledge of distance to the landing site to the helicopter pilot.

Bell, J. M. A landing display for use with a contact flight simulator. Port Washington, NY: Office of Naval Research, Special Devices Center, Contract N6ori-71, Task Order XVI, Technical Report 71-16-7, 1951.

Bergman, C. A., Sivier, K. R., and Roscoe, S. N. Control authority with a flight performance controller. Proceedings of the Seventeenth Annual Meeting of the Human Factors Society. Santa Monica, CA: Human Factors Society, 1973.

Beringer, D. B., Williges, R. C., and Roscoe, S. N. The transition of experienced pilots to a frequency-separated aircraft attitude display. Human Factors, 1975, 17, 401-414.

Bode, W. E., Kendricks, R. A., and Kane, E. J. Simulation and study of V/STOL landing aids for USMC AV-8 aircraft. Proceedings of the AGARD Guidance and Control Panel Symposium, The Hague, Netherlands. Neuilly-sur-Seine, France: North Atlantic Treaty Organization, 1979.

Bode and his colleagues discuss requirements for landing a V/STOL aircraft at a forward site or on an air-capable ship. They point out that both in landing and when thrust-vectoring is begun, an attitude hold autopilot would be beneficial to the pilot. From the results of a questionnaire study, they conclude that V/STOL aircraft pilots believe that an attitude hold autopilot, rate of descent information, and glideslope command steering would be especially useful landing aids.

Boehm-Davis, D. A., Curry, R. E., Wiener, E. L., and Harrison, R. L. Human factors of flight-deck automation--NASA/industry workshop. Washington, DC: National Aeronautics and Space Administration, Technical Memorandum TM-81260, 1981.

These authors point out that flight-deck functions are currently being automated for safety and economy reasons as well as because state-of-the-art microprocessor technology allows manufacturers to include automation as a standard feature. Automation allows functions to be done that otherwise could not be. These systems can also provide better solutions to problems than humans. However, there are problems with cockpit automation. Pilots are sometimes unwilling to engage automatic systems because they are not familiar with the system, have no faith in the system, or feel they will be relegated to the role of monitor when

the system is operating.

Bohret, H. GCU, The Guidance and Control Unit for all weather approach. Proceedings of the AGARD Guidance and Control Panel Symposium, The Hague, Netherlands. Neuilly-sur-Seine, France: North Atlantic Treaty Organization, 1979.

This report describes an MLS system for curved V/STOL aircraft landings. These landings were curved in both azimuth and elevation. The author's thesis is that such curved approaches are preferable to segmented linear ones because of their short capture and steep descent.

Brown, E. L., Matheny, W. G., and Flexman, R. E. Evaluation of the School Link as an aid to teaching ground reference maneuvers. Port Washington, NY: Office of Naval Research, Special Devices Center, TR SDC 71-16-8, 1950.

Carel, W. L. Pictorial displays for flight. Culver City, CA: Hughes Aircraft, Research and Development Division, Contract Nonr 4468(00), JANAIR TR-2732.01/40, 1965.

Clement, W. F. Predicting field-of-view requirements for V/STOL aircraft approach and landing. Proceedings of the Fifteenth Annual Conference on Manual Control. Wright State University, Dayton, OH: Air Force Flight Dynamics Laboratory, Report No. AFFDL-TR-79-3134, 1979.

In a mathematical treatment of this topic, Clement states that field-of-view requirements of the pilot of a V/STOL aircraft when viewing the recovery area are related to the location of the area on the ship, the aircraft orientation, and the relative position of the aircraft with respect to the ship. He notes that the FOV requirements are greatest near the recovery ship during hover and near the hover point. Further, he suggests the use of visual cues and aids above the [illegible] to decrease FOV requirements. Additionally, he points out that airwake turbulence of the ship may be a significant problem. Relating his analysis to manual versus automatic control tradeoff considerations, he suggests that V/STOL aircraft will need higher control authority than they have presently if the pilot's workload is to be lightened.

Collyer, S. C., Ricard, G. L., Anderson, M., Westra, D. P., and Perry, R. A. Field of view requirements for carrier landing training. Orlando, FL: Naval Training Equipment Center, Technical Report NAVTRAEQUIPCEN IH-319/AFHRL-TR-80-10, 1980.

These experimenters conducted a transfer of training experiment that measured performance of CTOL aircraft that had wide (300 deg x 150 deg) or narrow (48 deg x 36 deg) fields-of-view as they landed on a simulated aircraft carrier. Using a short practice time and experienced pilots, they could not find any performance variability related to the field-of-view that was presented to the pilots.

Conway, R. C. VTOL and STOL simulation study: Final report. Atlantic City, NJ: Federal Aviation Administration, National Aviation

Facilities Experimental Center, Report No. NA-68-21 (RD-67-68), 1968.

The FAA VTOL and STOL Simulation Study, which was primarily concerned with the integration of VTOL aircraft into terminal areas designed for regular aircraft, is described. The study analyzes glide-slopes and recommends, in effect, that these craft use the same approach and takeoff patterns as fixed-wing aircraft. This report is somewhat out of date and does not attempt to use the performance capabilities of VTOL craft to find a better terminal procedure.

Creelman, J. A. Evaluation of approach training procedures. Pensacola, FL: U.S. Naval School of Aviation Medicine, Project NM 001-109-107, Report 2, 1955.

Curtin, J. G. A helicopter flight evaluation of a head-up display. Paper presented at the Southwest Psychological Association Meeting, Arlington, TX, 1966.

From the results of two experiments with three pilot-subjects in each, the author concludes that the field-of-view was too small in the helicopter HUD that was studied and that this display was not sensitive enough.

Derrick, W. L. A multidimensional scaling study of operator work load dimensions. Proceedings of the Human Factors Society 25th Annual Meeting. Santa Monica, CA: Human Factors Society, 1981.

Dougherty, D., Emery, J. H., and Curtin, J. G. Comparison of perceptual work load in flying standard instrumentation and the contact analog vertical display. Fort Worth, TX: Bell Helicopter, JANAIR TR D228-421-019, 1964.

Dukes, T. A. Helicopter IFR flight path control system. Proceedings of the AGARD Guidance and Control Panel Meeting, Konstanz, Germany. Neuilly-sur-Seine, France: North Atlantic Treaty Organization, 1971.

This researcher analyzes the helicopter pilot's control task and states that, as a general principle, it is desirable for the pilot to be able to use the same control techniques in different flight modes. To adequately control his craft the pilot will have to determine his flight path error, decide on a control policy, and then control the aircraft. From experimental analysis, the author concludes that error rate information is most important for a pilot controlling an aircraft.

Elam, C. B. Television as an aid to helicopter flight. Fort Worth, TX: Bell Helicopter, TR D228-421-018/Nonr 1670(00), 1964.

Ellis, J. and Emery, J. Army Digital Avionics System (ADAS) human factors engineering final report, Volume II. Phoenix, AZ: Sperry Flight Systems, Sperry No. 91-1662-80-02, 1981.

Part II of the ADAS final report is almost exclusively concerned with the differences between display and control systems used in the UH-1H helicopter and those adapted for use in the newer UH-60 helicopter.

This Sperry/Bell report details the elements of the UH-1 controls and displays that were changed and how evaluation and measurement procedures in the human factors engineering cockpit analysis were modified for study of the systems in the UH-60.

No new researches or data are presented in this paper and no variables or proposed work are discussed. Technical information on the nature of the displays and the range of elements incorporated into UH-60 flight displays is not given. The reader is directed to Part I of this report for such information. Volume II also lacks information on glideslopes, VTOL craft, and related matters. It is primarily concerned with overall helicopter workload and new types of cockpit displays. Workload analysis sheets and diagrams of 11 UH-60 displays and controls are included, and are of value to anyone designing an overall cockpit control system for helicopters.

Ellis, J. and Fahy, B. ADAS control and display specifications (for UH-60). Phoenix, AZ: Sperry Flight Systems, Sperry No. 71-1662-72-01, 1981.

The ADAS (Army Digital Avionics System) is described in this report. Its purpose is to integrate the electrical and electronic subsystems of the UH-60A Blackhawk helicopter. It will provide fully integrated control and display capabilities for both crew members. Two CRTs will handle flight, interactive control/display, and navigation display functions.

The two major ADAS flight display modes are VSD and approach. The following VSD data will be displayed: caution/warning annunciation, heading, reference aircraft symbol, airspeed, turn rate, lateral trim, barometric altitude, radar altitude, vertical speed, roll, pitch, cyclic commmand, and collective command. Approach data to be displayed are caution/warning annunciation, heading, reference aircraft symbol, airspeed, ground plan (integrated heading, pitch, and roll required), flight path cue, lateral trim, barometric altitude, radar altitiude, vertical speed, roll, pitch, cyclic command, and collective command.

A ground plane consisting of a grid that rotates as the plane turns can also be displayed. The size of this grid is inversely proportional to the altitude of the aircraft. Its rotational speed is proportional to the plane's airspeed or ground speed (if the former is unavailable).

This display system's HSD has two modes: tactical and navigational. The navigation mode's data are a map display, present position, compass heading scale, heading marker, course bug, heading bug, map mode, VOR or TLS to/from indicator, reference aircraft mark, map scale, ground speed, time to next waypoint, distance to next waypoint, course, wind direction and velocity, radar altitude, annunciation data, and advisory messages. Its tactical data are the same as these, but with tactical symbols added to the set.

The Keyboard Terminal Unit is the main input device for the ADAS control/display subsystem. There is a Unit for each pilot. It can be used to aid navigation or in one of several other modes such as CEDI,

performance, ASE, secondary systems, engine status, command instrument system (CIS), or advisory/caution/warning/acknowledge.

The test plan for the ADAS is in Phase II; the CRT will be bench tested.

Emery, J. H. and Dougherty, D. Contact analog simulator evaluations: Vertical display with horizontal display. Fort Worth, TX: Bell Helicopter, JANAIR TR D228-421-020, 1964.

Fogel, L. J. A new concept: The kinalog display system. Human Factors, 1959, 1, 30-37.

Frank, L. H. Comparison of specifications for head-up displays in the Navy A-4M, A-7E, AV-8A, and F-14A aircraft. Pensacola, FL: Naval Aerospace Medical Research Laboratory, Special Report 79-6, 1979.

This reviewer provides a compendium of specifications for several types of military aircraft displays, including those for V/STOLs. From it we see that displays differ operationally from one plane to the next. These displays also differ considerably from the military specifications. Frank notes that one major problem reported by pilots is display clutter. He recommends an information processing analysis.

Frezell, T. L., Hofmann, M. A., and Oliver, R. E. Aviator visual performance in the UH-1H. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory, Report No. 74-7, 1973.

In a descriptive study rather than the traditional human factors experiment in which they monitored helicopter pilots' scan patterns during takeoff and landing, and various aspects of flight, Frezell, Hofmann, and Oliver report that these pilots look through the lower right windscreen more often than anywhere else and that during landing (whether in a right or left pattern) 70% of the pilots' scan time is spent in the lower right windscreen sector.

From their account, we see that the pilots' subjective ratings of the time spent looking through different parts of the windscreen correlate poorly with the facts. Because there was a time lag between the pilots' flights and their ratings, such a result might be suspected. These researchers also measured the frequency of the pilots' scan transitions from one windscreen sector to another and found that the most frequent transitions were from the lower right windscreen to inside the cockpit.

Gallaher, P. D., Hunt, R. A., and Williges, R. C. A regression approach to generate aircraft predictor information. Savoy, IL: University of Illinois at Urbana-Champaign, Aviation Research Laboratory, Technical Report ARL-76-11/ONR-76-2, 1976.

Multiple regression analysis as an alternative to complete fast-time predictor models is presented in this report of an experimental study done for the Office of Naval Research. These researchers developed such linear approximations for each of the six degrees of

freedom of aircraft motion and considered their technique to be satisfactory.

Gibson, J. J. The senses considered as perceptual systems. Boston: Houghton Mifflin, 1966.

Gibson, J. J., Olum, P., and Rosenblatt, F. Parallax and perspective during aircraft landings. American Journal of Psychology, 1955, 68, 480-484.

Gold, T. and Walchli, R. M. A head-up display for all-weather approach and landing of tilt-wing V/STOL aircraft. Great Neck, NY: Sperry Division, Sperry Rand Corporation, undated.

Gold and Walchli report an investigation of HUDs for V/STOL aircraft and note that field-of-view requirements for these displays are critical and that they may be cluttered with too much symbology. Additionally, in reference to the V/STOL aircraft pilot's control task they inform us that maintaining altitude during transition increases pilot workload.

Haarten, van der, R. J. Some aspects of offshore operations in the Netherlands. Proceedings of the AGARD Flight Mechanics Panel Symposium, Moffett Field, California. Neuilly-sur-Seine, France: North Atlantic Treaty Organization, 1978.

This report describes a display system that was developed to assist nighttime IFR operations in the North Sea. The author notes that rotor-winged aircraft are never committed to land, i.e., a pilot of such a craft can abort an approach at any time. This display was installed in a close-scan instrument panel so that a pilot may fixate only necessary instruments during low-speed takeoff and approach and landing. These display designers chose a close-scan layout to minimize the chance that a pilot would look out the window during these low-speed operations and become disoriented. Corollarily, van der Haarten remarks that HUDs are not effective for low-speed flight because of this.

In a discussion of icy flight conditions, he points out that engine torque is an indicator of the amount of blade icing. In conclusion, he recommends that terminal guidance for helicopters be augmented by approach and landing equipment, electronic integrated display systems, and specific helicopter avionics.

Hasbrook, A. H. The approach and landing: Cues and clues to a safe touchdown. Business and Commercial Aviation, 1975, November, 39-43.

Hart, S. G. and Loomis, L. L. Evaluation of the potential format and content of a cockpit display of traffic information. Human Factors, 1980, 22, 591-604.

Hart and Loomis studied the use of various symbols for CDTI displays. Based on interviews with flight related personnel and several experiments, they developed a set of symbols and a scale factor appropriate for future CDTI displays.

Hemingway, J. C. A pilot survey of human factors in V/STOL. Washington, DC: Naval Air Systems Command, Report No. A-531-78-1, 1978.

Hemingway recounts the results of a survey of V/STOL aircraft pilots. Its objectives were to identify human factors engineering deficiencies in V/STOL craft design, to decide on the adequacy of current design practices for V/STOL flight, to develop alternatives to V/STOL craft stabilization and control/display systems, and to determine what present V/STOL technologies could be augmented. The author's thesis is that pilot workload is high and that flight control response times are shorter in the acceleration control V/STOL aircraft system.

He finds that: (a) there is a need for improved, integrated HUDs, (b) out-of-tolerance logic should be used for advisory, caution, and warning displays, (c) critical performance variables should be displayed, (d) the control and display of thrust vector and power management should be improved, as should, (e) cockpit layout, and (f) attitude stabilization, and (g) accident data support these findings. He notes that these problems are exacerbated by current military specifications that emphasize CTOL not V/STOL craft. He concludes that considerable effort will be required to successfully address the V/STOL craft's unique requirements.

Hemingway points out several research and technology issues. Some of those related to displays are omni-directional landing aids, shipboard landing aids, VIFF, integrated displays (HSD-VSD, HUD), predictor displays, distance to go to hover information, vertical velocity, sideslip information, fuel remaining, and external FOV. Control related requirements include vertical velocity indication, integrated thrust vector/power management, computer-aided power management, and stability augmentation.

This report concludes with the following observations and recommendations: there is a void or gap between advanced technology and the unique V/STOL craft piloting factors; to bridge this gap a multidisciplinary effort for high- and low-speed craft and for IMC and VMC is required; and the review by Ringland et al. (1977) is a good jumping-off point from which to develop a data base for V/STOL craft.

Hennessy, R. T., Lintern, G., and Collyer, S. C. Unconventional visual displays for flight training. Orlando, FL: Naval Training Equipment Center, Technical Report NAVTRAEQUIPCEN 78-C-0060-5, 1981.

Hennessy, R. T., Sullivan, D. J., and Cooles, H. D. Critical research issues and visual system requirements for a V/STOL training research simulator. Orlando, FL: Naval Training Equipment Center, Technical Report NAVTRAEQUIPCEN 78-C-0076-1, 1980.

Hennessy and his fellow consultants begin their discussion of critical research issues for V/STOL aircraft by presenting some fundamentals. They note that V/STOL aircraft are capable of several types of takeoffs. During vertical takeoffs, and when the plane goes from thrust-borne to aerodynamic flight, maintenance of bank angle is

critical. Rolling takeoffs are made into the wind to avoid sideslip. Angle of attack is a critical variable when short takeoffs are made.

After reaching appoximately 25 feet, V/STOL aircraft may accelerate to what is known as transition. Here again the pilot must avoid slipping sideways. When a V/STOL aircraft lands vertically, the pilot must be careful not to stop in the ground effect. Sometimes to avoid damage to the landing area and ingestion of ground debris, rolling vertical landings are made. To land a V/STOL aircraft on a ship, the pilot matches the speed of the ship then lands on the port side not the stern.

An analysis of the V/STOL aircraft mission led these writers to conclude that whether the mission is subsonic-multimission or supersonic-fighter-attack there are no peculiar requirements other than those attendant on shipboard and shorebased launch and recovery of these planes. A large percentage of V/STOL aircraft accidents occur during their unique phases of flight even though a great deal of training time is devoted to them. Because of this, Hennessy et al. believe that simulator training of V/STOL thrust-borne tasks is advisable.

They discuss basic features of the V/STOL aircraft's environment that are relevant to simulator scene content. From this they can define information as the perceptual conclusions a pilot makes because they are relevant to his task. They point out that the principal routine demand on the pilot is to recognize the state of the aircraft system. Environmental information sources play a key role here, because the variability of the pilot's information is directly related to these sources.

The assessment of V/STOL craft display requirements is complicated by the fact that, according to Hennessy et al., there is no way to go from visual information requirements to the nature of sources required to provide information to pilots. Instead, the question is: What are the information affordance characteristics of the scene that should be simulated? Here, they recommend that information sources, not information requirements, be specified.

They also present a discussion of fidelity and realism and perceptual learning in simulators. Because people can generalize application of skills in different visual environments, and because this perceptual learning occurs faster than acquisition of basic skills, simulators need not be terrifically realistic. The question here is: How is information afforded by environmental sources, and how does the pilot acquire it?

Holzhauser, C. A., Morello, S. A., Innis, R. C., and Patton, J. M., Jr. A flight evaluation of a VTOL jet transport under visual and simulated instrument conditions. Washington, DC: National Aeronautics and Space Administration, Technical Note TN D-6754, 1972.

These investigators evaluated the performance of the Dornier DO-31 jet VTOL transport during transition, approach and vertical landing. They assume that a VTOL transport should be able to fly in IFR conditions and spend a minimum time in hover. They note that the approach

phase is most demanding. Related to this, they recommend a better control and display of lift. Also, during approach pilots are reluctant to deflect the control stick greatly because such a movement disengages the stabilization system. Because this system, which stabilizes pitch and roll, allows precision approach and safe vertical landing and is optimized for the hover task, one may appreciate the pilots' caution. Pilots favored a rate control of this system.

To further complicate the decelerating approach, the craft's responses to control inputs change during the course of this maneuver. Additionally, because of insufficient control from the lift engine modulation, pilots rated the DO-31's vertical descent and landing characteristics unacceptable. During critical phases of the maneuvers studied here, pilots were hampered because they could not tell when they were near a control limit. Such problems are exacerbated by the time it takes a pilot to acquire and track the glideslope, generally 20-30 seconds.

The pilots involved in this study considered the workload imposed on them during transition, approach and landing to be too great. ILS acquisition via a series of discrete steps is one maneuver that contributes to this high workload. Inability to see the touchdown area during vertical descent also made the pilots' task much more difficult. The ability to command pitch attitude with a button on the control stick helped to reduce the pilots' workload. The stabilization of pitch, yaw, and roll during transition also helped to reduce this workload. However, because of this stabilization, power management becomes the most important task of the pilot. The authors note that because of this the pilot needs a better display of available power or thrust. Finally, attitude stabilization is the major factor related to successful landings. Because of this pilots believe that it is mandatory.

Jensen, R. S. Prediction and quickening in perspective displays for curved landing approaches. Ph.D. dissertation, University of Illinois at Urbana-Champaign, 1979. (Dissertation Abstracts International, 1979, 40, 3996B).

Johnson, S. L. and Roscoe, S. N. What moves, the airplane or the world? Human Factors, 1972, 14, 107-129.

Johnston, S. R., White, G. R., and Cumming, R. W. The role of optical expansion patterns in locomotor control. American Journal of Psychology, 1973, 86, 311-324.

Kaul, C. E., Collyer, S. C., and Lintern, G. Glideslope descent-rate cuing to aid carrier landings. Orlando, FL: Naval Training Equipment Center, Technical Report NAVTRAEQUIPCEN IH-322, 1980.

Kaul, Collyer, and Lintern provided descent rate information to CTOL aircraft pilots using a FLOLS simulation. In one experimental condition pilots were shown indications of the difference between the actual descent rate and the descent rate that would maintain the current glideslope. Other pilots saw the descent rate correction needed. In this condition if the pilot were tracking the glideslope correctly or

returning to it satisfactorily, no error signal was displayed. They conclude that the second type of display of rate information we have described here is better.

Keane, W. P. and Milleli, R. J. Precise IFR hovering--an operational need and a feasible solution. Proceedings of the AGARD Guidance and Control Panel Meeting, Konstanz, Germany. Neuilly-sur-Seine, France: North Atlantic Treaty Organization, 1971.

Keane and Milelli present results of an experiment to assess displays to assist the precise IFR hovering of so-called flying cranes. These aircraft may create their own IFR conditions when they hover in dust or snow. These researchers compared the ability of three displays to assist a pilot in this task. One display was the Integrated Trajectory Error Display. It is an integrated display with a multi-colored CRT that shows the craft's geographical position, velocity vector, attitude, altitude, collective command, collective position and heading. The moving velocity vector allows rapid assessment of one's projected position and determination of the direction to move the cyclic to correct errors.

With this display, pilots were best at controlling load oscillations, load longitudinal distance from the desired hover point, and helicopter center of gravity longitudinal distance from the hover point. The authors conclude that it is necessary for the pilot to have ground velocity information. Finally, from interviews they found that pilots would accept an automatic hover device if it included a pilot controlled hover option.

Kelley, C. R., Mitchell, M. B., and Strudwick, P. H. Applications of the predictor displays to the control of space vehicles. Santa Monica, CA: Dunlap and Associates, Inc., 1964.

These analysts considered the feasibility of using predictor displays in spacecraft. From their experiments they found that predictor displays aided in tracking maneuvers, but did not in attitude maneuvers.

Langewiesche, W. Stick and rudder: An explanation of the art of flying. New York: McGraw Hill, 1944.

Lintern, G. Transfer of landing skills after training with supplementary visual cues. Human Factors, 1980, 22, 81-88.

Lintern, G. and Roscoe, S. N. Visual cue augmentation in contact flight simulation. In S. N. Roscoe. Aviation Psychology. Ames, IA: Iowa State University Press, 1980.

McElreath, K. W. An advanced guidance and control system for rescue helicopters. Proceedings of the AGARD Guidance and Control Panel Symposium, The Hague, Netherlands. Neuilly-sur-Seine, France: North Atlantic Treaty Organization, 1979.

McElreath talks about guidance and control in rescue missions. In rescues performed with helicopters: (a) great hover precision is neces-

sary, (b) the pilot's workload will substantially increase during the hover, (c) as the craft nears the sea the safety margin will decrease, (d) because of increased crew activity only one pilot will be available to fly the helicopter, and (e) there is usually inadequate low-speed air data or ground-referenced velocity data.

According to him, a typical rescue would proceed as follows: (a) the pilot would plan his final descent to be downwind of and facing the target, (b) he would descend, perhaps steeply, and decelerate to a hover, (c) then he would go from instruments to visual hover even though sufficient visual cues may be absent, (d) the pilot would maintain a precise hover, and (e) then he would leave safely. To accomplish this an avionics system should be manageable by one person, but accessible to both pilots. It should also respond to failures gracefully, not allow a single failure to produce a catastrophe, and be capable of completing the mission if part of it fails. Finally, for the pilot to be able to use the avionics system fully, his workload must be low.

McGee, J. and Harper, H. Advanced subsystem status monitor. Ft. Eustis, VA: Applied Technology Laboratory, U.S. Army Research and Technology Laboratory, Technical Report USAAVRADCOM TR-80-D-3, 1980.

These authors believe that a study of subsystem monitoring will help to identify ways to reduce the high workload experienced by pilots during all-weather or NOE flight. From their analysis, they recommend that display-by-exception logic be used for many subsystem variables, except rotor speed and power management and that separate display logic for different mission phases is not necessary. Based on nonexperimental evaluations they argue that their subsystem monitor (SSM) will (a) decrease crew workload, (b) increase mission effectiveness, (c) increase reliability, (d) increase maintainability, and (e) increase survivability. They suggest that this SSM be experimentally evaluated and its interaction with other cockpit systems be studied.

McMullen, F. D. Shipboard helicopter operating procedures. Washington, DC: Department of the Navy, Office of the Chief of Naval Operations, Report NWP42(B), 1976.

In a Navy procedures manual describing shipboard helicopter operations, we find a complete reference for the handling of helicopters on ships, giving full details on service procedures, signals, and chain of command. Some details for ship landings of helicopters can be found in this manual. Information about the following is in this report: (a) servicing helicopters on ships, including refueling, unloading weapons, and launch procedures; (b) deployment and operating procedures for helicopters used in conjunction with and from LPHs (amphibious assault ships); (c) helicopter search and rescue operations; (d) resupply of carriers or other ships by ship replenishment (UNREP) in conjunction with resupply from the air by helicopter (VERTREP); and (e) flight operations for antisubmarine warfare (ASW) and the Light Airborne MultiPurpose System (LAMPS) for electronic equipment.

Momiyama, T. S. Project NAVTOLAND (Navy Vertical Takeoff and Landing Capability Development). Proceedings of the AGARD Guidance and

Control Panel Symposium, The Hague, Netherlands. Neuilly-sur-Seine, France: North Atlantic Treaty Organization, 1979.

In his description of a proposed U.S. Navy research program, Momiyama says that from 1973 to 1978 there was no advance in helicopter or V/STOL aircraft capability in poor weather or rough seas. The reasons for this are the inadequate control system of the AV-8 Harrier; all-weather, precision landing-guidance systems are installed only on aircraft carriers; and there have been few researches dealing with all-weather V/STOL aircraft problems. This project's goals are to develop means that will permit V/STOL aircraft operation in Rough Sea State Five and zero ceiling and 700 feet visibility. Current operational minima are 400 feet and one nautical mile. The components of this program will be V/STOL aircraft and helicopters landing on 72 x 72 feet steel matted pads on land or on pads on air-capable ships. These ships may be cruisers, frigates, destroyers, aircraft carriers, helicopter carriers, or amphibious assault ships.

Concluding, Momiyama states that the V/STOL pilot needs visual landing aids, electronic guidance, and information about ship motion and ship airwake, including wind-over-the-deck, and accurate low airspeed indication. He suggests that this information could be gotten from integrated displays. Finally, but importantly, he notes that regarding air traffic control for V/STOL aircraft, they do not come in down a fixed glideslope; instead they transition, hover, and land.

Nethaway, J. E. The implications of operating helicopters in poor visibility. Proceedings of the AGARD Guidance and Control Panel Meeting, Konstanz, Germany. Neuilly-sur-Seine, France: North Atlantic Treaty Organization, 1971.

In an analysis of the implications of operating helicopters in poor weather, Nethaway notes that approaches in such conditions may have to be made on instruments to decrease pilot workload. He suggests using CRTs for HUD, VSD displays that show a horizon line, the site displacement, and the velocity vector. He believes that CRTs could also be used as HSD plan position indications of the helicopter's position relative to the landing site. He recommends an approach and landing aid similar to the FLOLS system used on U.S. aircraft carriers. This aid would consist of a T-bar of lights on the ground and glideslope indicator lights colored red, green, or amber. This aid would provide continuity of vertical information to the pilot as he goes from instruments to visual reckoning.

North Atlantic Treaty Organization, Advisory Group for Aerospace Research and Development. Displays for approach and landing of V/STOL aircraft. Neuilly-sur-Seine, France: Author, Advisory Report No. AGARD-AR-51, 1972. (a)

North Atlantic Treaty Organization, Advisory Group for Aerospace Research and Development. V/STOL displays for approach and landing. Neuilly-sur-Seine, France: Author, Report No. AGARD-R-594, 1972. (b)

Two AGARD reports include conclusions about the man-machine inter-

face in V/STOL aircraft. They begin by stating that it is generally thought that operation of V/STOL aircraft in poor weather should be safer than operation of CTOL planes, because V/STOL aircraft can fly slowly and stop if necessary. It is also assumed that all tactical military planes should be able to fly in adverse weather. Two other general considerations about V/STOL flight are that pilots may have to fly the entire approach and landing by instruments to exploit the operational advantages of these craft and that, because V/STOL aircraft use their propulsion systems for lift, display of thrust should be primary.

Under IMC V/STOL planes can fly variable landing profiles, which are dependent on limitations of the aircraft, tactical and environmental conditions, and the craft's present position relative to the landing point. These variable approach paths can save fuel and decrease the plane's exposure time. However, because of their low-speed, direct-lift characteristics, precise position information relative to the desired landing site is probably more important than position information relative to the glideslope. The authors also note that because of the need to fly steep curved approaches in a dense traffic environment, the pilot's workload will doubtlessly go up.

Next they consider the tradeoff between control and display sophistication. Here they mention that with their direct control of vertical acceleration, V/STOL planes can correct altitude errors immediately. Still, appropriate displays cannot be developed until we know what is to be controlled, operated, and monitored. Although researchers realize that vehicle stabilization should be automated, we are still ignorant of the information requirements for manual control because the human operator is so adaptable.

Concerning the V/STOL aircraft pilot's information requirements, these advisors believe that approach and landing will consist of an IMC stage and a final visual phase. Such maneuvers present several problems to the pilot. The authors discuss two of these and suggest solutions. First, they recommend that the pilot be relieved of the task of sideslip constraint. Second, landing V/STOL aircraft with zero lateral and longitudinal velocities and a low rate of descent is much more difficult than landing a CTOL plane. To do this the plane must be able to move in six degrees-of-freedom and consequently this information must be displayed to the pilot.

They list the following specific information needs: airspeed; ground speed and direction; height (with a finely graduated scale); vertical speed because of the constantly changing vertical velocities during a decelerating approach; pitch and roll angles; heading; angle of attack (noting that it has no significance in the sub-aerodynamic region of flight); sideslip or lateral velocity; range to landing site; time; available thrust and engine parameters because the pilot needs to know the condition of the engine just before landing, but cannot check it without disturbing the flight; thrust vector angle; and guidance information (remembering that V/STOL planes do not have to fly fixed glideslopes).

They preface a survey of V/STOL displays that were current then by

noting that conventional dial type displays are not acceptable for V/STOL planes. Here they state that the display of altitude error is hardest, the display of attitude should be central, and that rational display of altitude is intractable. They conclude that V/STOL displays should allow pilots to fly flexible approaches; to get pilot confidence in a display system, it must contain both director and situation displays; combined displays are needed to deal with all of the necessary information; and symbol geometry is of secondary importance, it is most important to display the correct information in a usable manner.

They end their report by recommending several areas for future research and development. These areas are: (a) how much effort the pilot puts into stabilization, (b) how pilots cope with changing effects of controls during transition from aerodynamic to thrust-borne flight, (c) what the range of possible V/STOL aircraft approaches is, (d) approach and landing under high crosswinds, (e) laterally and longitudinally curved approaches, (f) knowledge of maximum available thrust, (g) the relation between workload and the number of displays, (h) display of altitude information, and (i) field-of-view research.

Palmer, E. A., Jago, S. J., Baty, D. L., and O'Connor, S. L. Perception of horizontal aircraft separation on a cockpit display of traffic information. Human Factors, 1980, 22, 605-620.

These researchers investigated the effects of various CDTI symbologies on judgment of craft separation. They report that predictors improved performance, but that displayed history, viewing time, and update rate had no effect on performance.

Payne, T. A. A study of the moving part, heading presentation, and map detail on pictorial air navigation displays. Port Washington, NY: Office of Naval Research, Special Devices Center, Contract N6ori-71, Task Order XVI, Human Engineering Report SPECDEVCEN 71-16-10, 1952.

Payne, T. A., Dougherty, D. J., Hasler, S. G., Skeen, J. R., Brown, E. L., and Williams, A. C., Jr. Improving landing performance using a contact landing trainer. Port Washington, NY: Office of Naval Research, Special Devices Center, Contract N6ori-71, Task Order XVI, TR SPECDEVCEN 71-16-11, 1954.

Pitrella, F. D., Prosin, D. J., Kelley, C. R., and Wulfeck, J. W. Effect of a predictor display on carrier landing performance--Phase A (display development). Santa Monica, CA: Dunlap and Associates, Inc., 1971.

Pitrella et al. began a series of experiments to determine the effect of predictor displays on the performance of pilots landing CTOL aircraft on aircraft carriers. In their analysis they state that during these landings pilots must carefully monitor angle of attack and their position relative to the glideslope. Further, they point out that it is hard to correct glideslope errors late in the landing and still achieve the required terminal conditions. To assist the pilot during carrier landings they suggest that integrated information be presented. This

information should contain the following: glideslope reference, aircraft's flight path, relative motion rate between the flight path and the glideslope, line up information, angle of attack, heading, CVA ready deck, and roll and yaw angles.

Prosin, D. J., Burger, W. J., and Wulfeck, J. W. Effect of a predictor display on carrier landing performance--Phase B (display mechanization and preliminary evaluation). Santa Monica, CA: Dunlap and Associates, Inc., 1972.

Prosin et al. developed a predictor display system that had a glideslope predictor tunnel made of a series of rectangles. The far end movement of this figure resembles that of a carrier's near end. The tunnel starts 1 1/4 miles from the carrier and ends at the number three landing wire. Its perspective is perceptually accurate. Several different error measurements can be made with this system.

Ringland, R. F. An introduction to V/STOL technology affecting the pilot's role. China Lake, CA: Naval Weapons Center, Report No. NWC TP 5996, 1977.

This report describes V/STOL aircraft in general, gives examples of them, defines disk loading, and discusses turbine engines. In it the author also discusses control differences among CTOL craft, V/STOL craft, and helicopters. This report is a introduction to V/STOL aircraft and also supports the thesis of the following report, viz., that the high pilot workload associated with flying V/STOL planes is due to their inherent instability and the fact that the pilot must attend to more control related duties than when he is flying a CTOL craft.

Ringland, R. F., Craig, S. J., and Clement, W. F. Survey of piloting factors in fixed-wing V/STOL aircraft design. China Lake, CA: Naval Weapons Center, Report No. NWC TP 5941, 1977.

Ringland, Craig, and Clement present a comprehensive review of V/STOL aircraft design facets that affect the pilot's task. They note that currently a wide variety of manipulator concepts are used for control of these aircraft. Additionally, the pilot must stabilize the plane throughout the entire conversion (transition) from aerodynamic to thrust-borne flight and vice versa. Also, nowadays, the pilot's high level of skill is used to achieve system safety and reliability. These factors combine to overload the V/STOL aircraft pilot perceptually, cognitively, and at the psychomotor level.

These analysts point out several general technological attributes of V/STOL planes that directly affect the pilot's control task. The primary one of these is that V/STOL planes can convert from aerodynamic to thrust-borne flight by means of a change in the physical configuration of the plane. In the V/STOL flight regime, more fuel must be saved for approach and landing than in CTOL flight. Likewise related to approach and landing is the fact that there are physical limits on how fast and steeply a V/STOL ship can descend.

The CTOL airplane pilot is most interested in controlling his

craft's velocities, however when a V/STOL plane is flying slowly in an approach its pilot needs to control the craft's position not its velocity. At that time, the difficulty of the pilot's task is compounded because the meanings of changes in the values of some variables interchange. Furthermore, the attitude, flight path, and speed/stability characteristics of V/STOL planes change during transition. Because of these low speeds, V/STOL aircraft are particularly susceptible to disturbances such as wind shears, and several different ground effects, viz., attitude trim changes, dust or water clouds, and hot gas ingestion.

According to Ringland et al. there are features of specific aircraft that produce high pilot workload. They are a result of design philosophies that stress flexibility and thus assign many tasks to the the V/STOL pilot rather than to the plane itself. A V/STOL aircraft pilot must attend to the following tasks: configuration scheduling and lift/thrust management; attitude stabilization; subsystem failure management; and path, speed, and position control and regulation. Although the CTOL aircraft pilot must also concern himself with these tasks, he is not continuously responsible for them--the V/STOL aircraft pilot is. Additionally, the V/STOL airplane pilot's traditional role is more complex; he has more variables to control more closely.

From this, Ringland and his colleagues conclude that there has been an inappropriate assignment of V/STOL pilot/vehicle system functions to the pilot. As a result, the pilot is overloaded. They suggest that henceforth the human factors engineer involved in the design of V/STOL aircraft should concern himself with unloading the pilot while maintaining adequate pilot/vehicle performance.

These authors also discuss the V/STOL aircraft pilot's information requirements. When the pilot is controlling the flight path of the aircraft he needs information about variables that are related to a particular mission segment. The pilot also needs to be aware of the aircraft system's health and safety. Currently, such information is not displayed and thus the pilot does not have a specific information source to tell him how close to loss of control he is.

They also note some system aspects that relate to piloting V/STOL aircraft. First, they point out that current workload assessment is poor. Attitude stabilization and flight path response qualities are needed before we can talk about any control/display tradeoff. Pilots will now accept more vehicle automation. More research needs to be done about shipboard and forward site recovery.

From their analysis, Ringland and his associates conclude that: (a) control aspects of V/STOL aircraft produce the well-recognized problem of excessive pilot workload; (b) the problems in controlling V/STOL craft cannot be overcome by display improvement alone because this would lead to too much information processing by the pilot; (c) existing automation and augmentation technology can solve the problems and get pilot acceptance; (d) precise specific corrections are possible; (e) a control/display tradeoff point will not be reached until certain vehicle stability and controllability minima are reached; (f) even a sophisticated, integrated HUD will not solve the problem without exces-

sive pilot workload; and most fundamentally (g) the conversion from aerodynamic to thrust-borne flight produces all the V/STOL craft's unique characteristics, including those involving human factors.

In addition to its references, this report contains a list of supplemental references and an annotated bibliography, all of which are extensive.

Roscoe, S. N. Flight by periscope: I. Performing an instrument flight pattern; the influence of screen size and image magnification. University of Illinois Bulletin, 1951, 48(55) (Aeronautics Bulletin No. 9).

Roscoe, S. N. The navigation director: An area navigation system. In R. J. Hornick (Ed.), Human factors in aviation. North Hollywood, CA: Western Periodicals, 1968.

Roscoe, S. N. Display-control synthesis. In S. N. Roscoe. Aviation psychology. Ames, IA: Iowa State University Press, 1980.

Roscoe, S. N. Landing airplanes, detecting traffic, and the dark focus. Aviation, Space, and Environmental Medicine, 1982, 53, in press.

Roscoe, S. N. and Bergman, C. A. Flight performance control. In S. N. Roscoe. Aviation psychology. Ames, IA: Iowa State University Press, 1980.

Roscoe, S. N., Corl, L., and Jensen, R. S. Flight display dynamics revisited. Human Factors, 1981, 23, 341-353.

Roscoe, S. N., Hasler, S. G., and Dougherty, D. J. Flight by periscope: Making takeoffs and landings; the influence of image magnification, practice, and various conditions of flight. Human Factors, 1966, 8, 13-40.

Roscoe, S. N. and Jensen, R. S. Computer-animated predictive displays for microwave landing approaches. IEEE Transactions on Systems, Man, and Cybernetics, 1981, SMC-11, 760-765.

Roscoe, S. N., Johnson, S. L., and Williges, R. C. Display motion relationships. In S. N. Roscoe. Aviation psychology. Ames, IA: Iowa State University Press, 1980.

Roscoe, S. N. and Kraus, E. F. Pilotage error and residual attention: The evaluation of a performance control system in airborne area navigation. Navigation, 1973, 20, 267-279.

Roscoe, S. N., Smith, J. F., Johnson, B. E., Dittman, P. E., and Williams, A. C., Jr. Comparative evaluation of pictorial and symbolic VOR displays in the 1-CA-1 Link trainer. Washington, DC: Civil Aeronautics Administration, Division of Research, Report 92, 1950.

Scolatti, C. A. Progress of the USAF inflight program: Low-speed con-

trol to landing on instruments in helicopters. Proceedings of the AGARD Guidance and Control Panel Meeting, Konstanz, Germany. Neuilly-sur-Seine, France: North Atlantic Treaty Organization, 1971.

Scolatti begins this exposition by complaining that the helicopter is still a VFR aircraft. Continuing, he points out that helicopters must use fixed-wing procedures when operating IFR in terminal areas. Finally, he informs us that the helicopter has the worst ratio of inherent operational potential to realized potential of any weapon system in the Air Force's inventory. He then discusses the low-speed regime of the helicopter and says that a relatively small proportion of a flight is spent there. From this he surprisingly concludes that no special purpose display of low speeds is warranted, and that existing displays should be modified if such velocity indications are to be shown to the pilot.

He describes an ongoing USAF study of low-speed approach to landing. Based on results of this program, he recommends the following low-speed flight aids: flight directors, situation displays, a specially designed cyclic controller, fully automated yaw axis control to decrease the pilot's workload, and additional unburdening in the collective dimension via automatic pilot assist systems.

Skaar, T. Air-sea rescue operations: Search and rescue experience. Proceedings of the AGARD Flight Mechanics Panel Symposium, Moffett Field, California. Neuilly-sur-Seine, France: North Atlantic Treaty Organization, 1978.

Skaar discusses aspects of air-sea rescue operations. From his version of a typical rescue, we learn that the pilot must see the survivors to rescue them, but during hover he cannot see them. This is especially bad because hover is the most critical phase of the rescue. To position the craft correctly, the pilot must rely on commands from the winch operator who is able to see the survivors. Skaar suggests that to solve this problem, the pilot might face rearward. This approach has appeal because it would avoid the use of elaborate electronic equipment. Alternatively, in some helicopters, the winch operator is able to maneuver the ship with a small control stick. This solution is not advisable, because the winch operator is not a pilot, and he must operate the winch. Therefore, Skaar concludes that an automatic altitude hold is needed.

Power considerations are also important in air-sea operations. Sea salt can condense on the engine's compressor blades and lead to compressor stall and then engine stall and finally power loss. It is difficult for a pilot to monitor engine power because he must induce an indication of it from engine torque, engine compressor rpm, and exhaust temperature readings. If the temperature increases while the others remain constant, there is most likely salt (or ice) build up. To complicate matters, during high winds the engine power fluctuates rapidly. Add to this the fact that the pilot is already very busy and one can easily see the difficulty of the situation. To relieve the pilot's workload, Skaar recommends the introduction of an engine performance indicator.

Sweeney, J. S., Bailey, A. W., and Dowd, J. F. Comparative evaluation of three approaches to helicopter instrumentation for hovering flight. Washington, DC: Naval Research Laboratory, Report No. 4954, 1957.

In this seminal report, Sweeney et al. point out that the helicopter is an unstable craft, especially at low speeds and in hovering maneuvers. They conducted a research program to determine the differential effectiveness of three types of instrumentation in reducing pilot workload, increasing the use of correct controls, and reducing error. They report that quickened, integrated, and conventional displays produced errors in the ratio of 1:4:6 in a simple helicopter hovering simulation. Addition of a secondary side task (e.g., the requirement to deal with cross winds or buffeting winds) increased error rates for pilots using all display types, but the ratio of errors remained the same. They conclude that quickened displays (of ground speed with integrated horizon) are best, pointing out that the helicopter pilot's task should be kept as simple as possible.

Systems Control, Inc. Candidate CDTI procedures study. Hampton, VA: NASA Langley Research Center, 1980.

This organization presents an overview of cockpit display of traffic information (CDTI) candidate procedures for NASA's Langley Research Center in which the primary uses of CDTI are outlined. These include merging and spacing of aircraft, weather avoidance deviation, and missed approaches and crossed paths. Using a modified CDTI display in VTOL aircraft, it would be possible to improve flight performance in a number of operational areas. By providing pilots with information about other craft, safety can be increased even when separation of craft is decreased and several planes are converging on a single point. This is extremely important when VTOL craft are taking off or landing at remote, unimproved sites under IFR conditions. Since CDTI can speed traffic flow, especially under IFR conditions, military VTOL maneuvers could be speeded by incorporating CDTI into VTOL aircraft.

Walk, R. D. and Gibson, E. J. A comparative and analytical study of visual depth perception. Psychological Monographs, 1961, 75 (Whole No. 519).

Wellern, W. Some problems in the development of an automatic flight control system for light helicopters. Proceedings of the AGARD Guidance and Control Panel Meeting, Konstanz, Germany. Neuilly-sur-Seine, France: North Atlantic Treaty Organization, 1971.

In a study of helicopter automatic control systems, Wellern analyzes the pilot's control task. He states that the pilot's work consists of stabilization of the generally unstable helicopter, attending to guidance related duties, and navigation and monitoring of subsystems. The pilot's control task is hampered because during IFR flight he does not receive sufficient information on flight conditions from flight sensors and conventional instruments. Therefore, stabilization of the ship is difficult or impossible. Thus, Wellern concludes that the main function of an automatic flight control system should be aircraft stabilization.

Wiener, E. L. and Curry, R. E. Flight-deck automation: Promises and problems. Washington, DC: National Aeronautics and Space Administration, Technical Memorandum TM-81206, 1980.

Wiener and Curry discuss the implications of cockpit automation. They point out that it is the current sophistication of microprocessor technology that allows many flight-deck functions to be automated. Besides its human factors advantages, flight-deck automation brings with it some problems. Wiener and Curry list several of these and conclude that the question is not whether a particular cockpit function can be automated, but rather should it be automated given that there is a human operator in the system?

Williams, A. C., Jr. Discrimination and manipulation in flight. In S. N. Roscoe. Aviation psychology. Ames, IA: Iowa State University Press, 1980.

Williams, A. C., Jr. and Roscoe, S. N. Evaluation of aircraft instrument displays for use with the omni-directional radio range. Washington, DC: Civil Aeronautics Administration, Division of Research, Report 84, 1949. (Abbreviated version as Journal of Applied Psychology, 1950, 34, 123-130.)

Wulfeck, J. W., Prosin, D. J., and Burger, W. J. Effect of a predictor display on carrier landing performance--Part I: Experimental evaluation. Inglewood, CA: Dunlap and Associates, Inc., 1973.

Wulfeck, Prosin, and Burger evaluated a predictor display system developed at Dunlap and Associates with a repeated measures experiment that included two other types of displays and used experienced carrier pilots as participants. Briefly, they found that the variability in the pilots' vertical and lateral errors was most uniform down the glideslope with the predictor display.

When they conducted this experiment, the following were "universally accepted" as cues to the estimation of altitude and altitude error: the horizon and its changes with the landing area and sea texture and its associated changes. They included a baseline display in their study which had none of the above, but did elicit pilot landing behavior which was very similar to actual landing performances in the fleet. This auxiliary finding thus contradicts ideas about the classical notion of perceptual cues.

Wulfeck, J. W. and Queen, J. E. The effect of lighted deck shape on night carrier landing: Final report. Inglewood, CA: Dunlap and Associates, Inc., 1975.

Wulfeck and Queen continued earlier work on the effect of the shape of an aircraft carrier's lighted deck on CTOL landing performance. They required experimental participants to judge when pitching decks with different lighting treatments were level. From the results of this experiment they developed a deck lighting scheme that should eliminate the conflict between information from a lighted deck and that from the

FLOLS system.

Wulfeck, J. W., Queen, J. E., and Kitz, W. M. The effect of lighted deck shape on night carrier landing. Inglewood, CA: Dunlap and Associates, Inc., 1974.

Wulfeck and his associates studied the effect of the shape of an aircraft carrier's lighted deck on CTOL aircraft landing performance. They were motivated by the fact that glideslope information from lighted decks is different from that provided by the FLOLS landing system. This conflict leads to a height illusion for pilots. The result is that pilots fly lower glideslopes with deck lighting than with the FLOLS system. Different deck lighting treatments will also cause pilots to fly different glideslopes. After experimental investigation of this phenomenon, they suggest that such variable behavior could be the result of judgment accuracy of the vertical in the frontoparallel plane that is poorer than judgment accuracy of the horizontal in the ground plane.

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Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

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Arlington, VA 22217

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Code 433
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

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Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

Dr. Robert G. Smith
Office of the Chief of Naval
Operations, OP987H
Personnel Logistics Plans
Washington, D.C. 20350

Dr. W. Mehuron
Office of the Chief of Naval
Operations, OP 987
Washington, D.C. 20350

Naval Training Equipment Center
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Human Factors Department
Code N-71
Naval Training Equipment Center
Orlando, FL 32813

Dr. Michael Melich
Communications Sciences Division
Code 7500
Naval Research Laboratory
Washington, D.C. 20375

CDR Robert Biersner
Naval Medical R&D Command
Code 44
Naval Medical Center
Bethesda, MD 20014

Dr. George Moeller
Human Factors Engineering Branch
Submarine Medical Research Lab
Naval Submarine Base
Groton, CT 06340

Head
Aerospace Psychology Department
Code L5
Naval Aerospace Medical Research Lab
Pensacola, FL 32508

Dr. James McGrath
CINCLANT FLT HQS
Code 04E1
Norfolk, VA 23511

Dr. S. Schiflett
Human Factors Section
Systems Engineering Test
Directorate
U.S. Naval Air Test Center
Patuxent River, MD 20670

CDR C. Hutchins
Code 55
Naval Postgraduate School
Monterey, CA 93940

Mr. J. Barber
HQS, Department of the Army
DAPE-MBR
Washington, D.C. 20310

Technical Director
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

CDR Norman E. Lane
Code N-7A
Naval Training Equipment Center
Orlando, FL 32813

Dr. Robert Blanchard
Navy Personnel Research and
Development Center
Command and Support Systems
San Diego, CA 92152

Mr. Stephen Merriman
Human Factors Engineering Division
Naval Air Development Center
Warminster, PA 18974

Dr. Julie Hopson
Human Facors Engineering Center
Naval Air Development Center
Warminster, PA 18974

Mr. Jeffrey Grossman
Human Factors Branch
Code 33152
Naval Weapons Center
China Lake, CA 93555

Human Facors Engineering Branch
Code 1226
Pacific Missile Test Center
Point Mugu, CA 93042

Dean of Academic Departments
U.S. Naval Academy
Annapolis, MD 21402

Chief, Systems Engineering Branch
Human Engineering Division
USAF AMRL/HES
Wright-Patterson AFB, OH 45433

Dr. Earl Alluisi
Chief Scientist
AFHRL/CCN
Brooks AFB, TX 78235

Director, Human Factors Wing
Defense & Civil Institute of
Environmental Medicine
Post Office Box 2000
Downsview, Ontario M3M 3B9
Canada

Director, Organizations and
System Research Labortory
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Technical Director
U.S. Army Human Engineering Labs
Aberdeen Proving Ground, MD 21005

Dr. Craig Fields
Director, System Sciences Office
Defense Advanced Research Projects
Agency
1400 Wilson Blvd
Arlington, VA 22209

Dr. Lloyd Hitchcock
Federal Aviation Administration
ACT 200
Atlantic City Airport, NJ 08405

Dr. M. Montemerlo
Human Factors & Simulation
Technology, RTE-6
NASA HQS
Washington, D.C. 20546

Dr. Robert R. Mackie
Human Factors Research Division
Canyon Research Group
5775 Dawson Avenue
Goleta, CA 93017

Dr. Robert T. Hennessy
NAS - National Research Council (COHF)
2101 Constitution Ave., N.W.
Washington, D.C. 20418

Dr. Amos Freedy
Perceptronics, Inc.
6271 Variel Avenue
Woodland Hills, CA 91364

Dr. Robert Williges
Dept. of Industrial Engineering & OR
Virginia Polytechnic Institute
and State Universtiy
130 Whittemore Hall
Blacksburg, VA 24061

Dr. Robert Fox
Department of Psychology
Vanderbilt University
Nashville, TN 37240

U.S. Air Force Office of Scientific
Research
Life Sciences Deirctorate, NL
Bolling Air Force Base
Washington, D.C. 20332

Defense Technical Information Center
Cameron Station, Bldg.
Alexandria, VA 22314 (12 cys)

Dr. Jesse Orlansky
Institute for Defense Analyses
1801 N. Beauregard Street
Alexandria, VA 22311

Dr. T. B. Sheridan
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

Dr. Arthur I. Siegel
Applied Psychological Services, Inc.
404 East Lancaster Street
Wayne, PA 19087

Dr. Harry Snyder
Department of Industrial Engineering
Virginia Polytechnic Institute and
State University
Blacksburg, VA 24061

Dr. James H. Howard, Jr.
Department of Psychology
Catholic University
Washington, D.C. 20064

Dr. William Howell
Department of Psychology
Rice University
Houston, TX 77001

Dr. Christopher Wickens
Universtiy of Illinois
Department of Psychology
Urbana, IL 61801

Dr. Edward R. Jones
Chief, Human Factors Engineering
McDonnell-Douglas Astronautics
Company
St. Louis Division
Box 516
St. Louis, MO 63166

Dr. Charles Gettys
Department of Psychology
University of Oklahoma
455 West Lindsey
Norman, OK 73069

Dr. Babur M. Pulat
Department of Industrial Engineering
North Carolina A&T State University
Greensboro, NC 27411

Dr. A. K. Bejczy
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91125

Dr. Stanley N. Roscoe
New Mexico State University
Box 5095
Las Cruces, NM 88003

Mr. Joseph G. Wohl
Alphatech, Inc.
3 New England Industrial Park
Burlingon, MA 01803

Dr. Rex Brown
Decision Science Consortium
Suite 721
7700 Leesburg Pike
Falls Church, VA 22043

Dr. William R. Uttal
Institute for Social Research
University of Michigan
Ann Arbor, MI 48109

Dr. Gary Poock
Operations Research Department
Naval Postgraduate School
Monterey, CA 93940

Mr. H. Talkington
Ocean Engineering Department
Naval Ocean Systems Center
San Diego, CA 92152

Mr. Edward M. Connelly
Performance Measurement
Associates, Inc.
410 Pine Street, S.E.
Suite 300
Vienna, VA 22180

Dr. Lola Lopes
Information Sciences Division
Department of Psychology
University of Wisconsin
Madision, WI

Dr. Richard Pew
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, MA 02238

Dr. David J. Getty
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, MA 02238

Dr. Douglas Towne
University of Southern California
Behavioral Technology Laboratory
3716 S. Hope Street
Los Angeles, CA 90007

Dr. Wayne Zachary
Analytics, Inc.
2500 Maryland Road
Willow Grove, PA 19090

Commanding Officer
ONREAST Office
ATTN: Dr. J. Lester
Barnes Building
495 Summer Street
Boston, MA 02210

Naval Material Command
NAVMAT 0722 - Rm. 508
800 North Quincy Street
Arlington, VA 22217

Dean of Research Administration
Naval Postgraduate School
Monterey, CA 93940

Mr. Warren Lewis
Human Engineering Branch
Code 8231
Naval Ocean Systems Center
San Diego, CA 92152

Dr. Ross L. Pepper
Naval Ocean Systems Center
Hawaii Laboratory
P.O. Box 997
Kailua, HI 96734

CAPT Richard L. Martin, USN
Commanding Officer
USS Carl Vinson (CVN-70)
Newport News Shipbuilding/Dry Dock Co.
Newport News, VA 23607

Commander
Naval Air Systems Command
Human Factors Programs
NAVAIR 340F
Washington, D.C. 20361

Commander
Naval Air Systems Command
Crew Station Design,
NAVAIR 5313
Washington, D.C. 20361

Mr. Phillip Andrews
Naval Sea Systems Command
NAVSEA 0341
Washington, D.C. 20362

Dr. A. L. Slafkosky
Scientific Advisor
Commandant of the Marine Corps
Code RD-1
Washington, D.C. 20380